Sudan University of Science and Technology
College of Graduate Studies
Department of Biomedical Engineering

Design of a Simple and Low Cost Electrical Impedance Tomography System using Arduino: Proteus Simulation

تصميم نظام التصوير المقطعي للمعاوقة الكهربائية البسيط والمنخفض التكلفة بإستخدام الأردوينو:محاكاه البروتوس

A project submitted in partial fulfillment for the requirements of degree of M.Sc. in biomedical engineering

By:
Manal Mustafa Mohamedali Mohamed
B.Sc. (Honours) Biomedical Engineering, Sudan University of Science and Technology (2014)
Supervisor:
Dr. Musab Elkheir Salih

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الآيـــــــــــه

بسم الله الرحمن الرحيم

قال تعالى:

{قَالُواْ سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ}

سورة البقرة (32)

Dedication

To my dear mother,

father,

sister,

brothers,

teachers,

and my friends for their patience and encouragement.

To every person hope to see mesuccessful,

with love and respect.

Manal

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I would like to express my special thanks to my supervisor **Dr. Musab Elkheir Salih**who gave me help, support and motivations until completion of this study. Also I am very gratitude to him for giving me this opportunity to do this project.

Also, I would like to express my thankfulness to **Dr. Mohamed A.A. Ahmed** who had always being there with helping hands and golden advices throughout the period of my work.

ABSTRACT

Electrical Impedance Tomography (EIT) is a new imaging technique that has the ability to image human body without prolonged exposure to radiations. Developing countries like Sudan suffers from the availability of imaging devices due to its high cost and its danger to health due to the use of ionizing radiation. This problem can be solved by designing a simple and low cost radiation free medical imaging system. Wehave designed an Arduino-based EIT system for radiation free medical imaging. This system consists of AC voltage generator, Voltage Controlled Current Source,16 electrodes andan automatic electrode switching module. Control of the system is achieved by Arduinowhich decreases the overall cost of the system while adding simplicity to the design. The system results in 208 voltage measurementswhich are processed in MATLAB interfaced with EIDORS (Electrical Impedance and Diffuse Optical Tomography Reconstruction Software) to reconstruct the image.

The proposed EIT system costs and performance are clearly discussed with tables and figures, it costsonly about 63.61 $, have an accuracy of 86.85% and reconstructs images with high resolution making it possible to have an alternative cheap ,accurate and simple EIT system forradiation free medical imaging.

المستخلص

المسح الطبقي للممانعة الكهربائية هي تقنيه تصوير جديدة لها المقدرة على تصوير جسم الإنسان بدون تعريضه مطولا للإشعاع المؤين. الدول النامية مثل السودان تعاني من توفر أجهزة التصوير نتيجه لتكلفتها العالية وخطورتها على الصحهبسبب إستخدام الأشعه المؤينه. هذه المشكله يمكن حلها بتصميم منظومة تصوير طبي بسيطه وقليلة التكلفة بدون أشعه مؤينه. قمنا بتصميم منظومة مسح سطحي للممانعة الكهربائيه اعتمادا على Arduino. هذه المنظومة تتكون من مصدر جهد متردد ، مصدر تيار يحكمه مصدر جهد ،عدد16 الكترود و وحدة تبديل تلقائي للإلكترودات.التحكم في المنظومة يتم عن طريق متحكم Arduinoالذي يقلل من التكلفة الكليه للمنظومة ويضيف البساطه للتصميم .المنظومة تنتج 208 جهدمقاس يتم معالجت ه عن طريق برنامج MATLABمربوط ببرنامجEIDORS لتكوين الصورة.

تكلفة و أداء هذه المنظومة نوقشت بوضوح بإستخدام الجداول والأشكال ، هيتكلف حوالي **63.61** دولار فقط، لها دقة تساوي86.85% وتقوم بتكوين صوره عالية الإستبانه مما جعل هنالك إمكانيه للحصول على منظومة مسح طبقي للممانعة الكهربائيهقليلة التكلفة، دقيقة وبسيطه للتصوير الطبيبدون أشعه.

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INTRODUCTION

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INTRODUCTION

1.1 Introduction

Electrical impedance tomography (EIT) is one of the medical imaging techniques that does not use any ionizing radiation to produce an image. EIT depends on the conductivity (conductance) of the human tissue which is different for different tissues. The conductance depend on the resistivity (or impedance) of the tissue to the current flow which is also different for different tissues (Joseph, 2000; Mould and Wbester, 1988; Gabriel *et al*, 1987). So EIT use this variation in impedance between tissues to produce an image.

EIT technique apply a current - As human cell acts like capacitor (Webster and John , 2010)the behavior of the tissue impedance depend on the frequency of the applied current- to human tissue and according to the conductivity distribution of the tissue, the potential distribution is measured in order to produce the image. There is direct relationship between the applied current pattern, conductivity distribution of the tissue and the potential distribution, so by knowing the applied current and the conductivity distribution of the tissue, the resistance of the tissue to the current flow can be measured which is then used to measure the potential distribution-this is called forward solution (Joseph, 2000; David, 2005). Another solution is the inverse solution where conductivity distribution of the tissue is unknown, obtaining sufficient information to determine it can be done by applying different current pattern-practically this can be done by using finite number of electrodes that apply different current patterns-and their corresponding voltages are measured. Current patterns and their corresponding voltages are then used to obtain a transformation matrix which represents the transformation of conductivity values to voltage values. Practically voltages are measured between each electrode and a reference electrode (which takes a value of zero) or between adjacent pairs of electrodes as shown in figure 1.1. (Joseph, 2000).Data (voltages) collected is used to produce the image using image reconstruction approaches.

For assessing the performance of EIT systems, phantoms can be used. There are two types of phantoms, physical phantoms which consist of a liquid or solid conductive

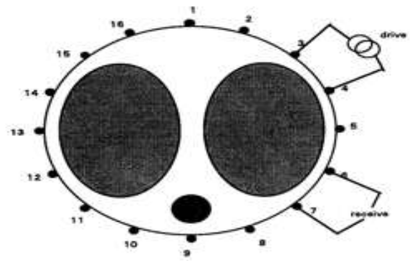


Figure1. 1:voltage measurements by adjacent electrodes

medium that can be imaged by an EIT system using surface electrodes. The conductive medium usually consists of a conductive gel or a saline solution inside which are inserted targets whose conductivity contrasts with that of the medium. The second type is mesh phantoms are composed of impedance elements interconnected in a particular topology. Resistors (Griffith, 1988; Hahn*et al.,* 2000; Hahn *et al.*, 2008) combinations of capacitors and resistors (Griffiths, 1995; Schneider,2000) as well as active electronic components (Schneider*et al.*,2000; Kleffel*et al.*, 2000) have been used as impedance elements.

EIT has many properties, it is a noninvasive and Safe technique (does not emit any ionizing radiation, based on difference in dielectric properties between healthy and malignant tissue), so it can be used for pregnant women (Matthew, 2014; Murari*et al.*, 1993, Mehrnoosh and Latiffah, 2015). Also EIT Imaging tool has low cost compared to those use ionizing radiation (Murari*et al.*,1993, Mehrnoosh and Latiffah,2015)and its data can be collected very rapidly so that changes in function can be measured and can produce thousands of images per second (Mohd, 2009).EIT can be used for Long term monitoring of physiological functions (can be used as a bedside real-time monitoring system which is affordable in hospitals and clinic) (Harikumar*et al*.; Brown, 2003). EIT devices are portable (EIT Imaging tool can be made of a light weight components, so screening can be done anywhere)(Mehrnoosh and Latiffah, 2015), Pain free (for example EIT for detection of breast cancer is comfortable compared to other technique because it is a non-compressive technique)(Zain and Kanaga, 2015), has High temporal resolution (Andy and Alistair, 2017)can reduce mortality (a good technique for early detection of tumors for example early detection of breast cancer for different ages and different breast sizes) (Matthew, 2014) and are easy to be operated and maintained (Harikumar*et al.*, 2013).

1.2 Problem statement:

Developing countries suffers from the availability of imaging devices due to its high cost and its danger to health due to the use of ionizing radiation.

1.3 Objectives:

1.3.1 General objective:

Design of a simple and low cost Arduino based Electrical impedance tomography (EIT) systemusing Proteus simulation.

1.3.2 Specific objectives:

- Simulate a two dimensional, 16 electrode Arduino based EIT system using Proteus simulation.
- Simulate two resistive phantom using Proteus simulation for checking EIT system.
- Presenting EIT images for (a) A perfectly homogeneous tissue (normal). (b) Non homogeneous Tissue.And discuss simulated result.

1.4 Proposed Methodology:

The proposed EIT system injects electrical current to human tissue and read the resulted voltage to be use for reconstructing an image. The current is generated using voltage generator and voltage controlled current sourceand injected using16 electrode. These 16 electrodes are selected through four multiplexors which are controlled by Arduino. Then Arduino reads the resulted voltages and send it to PC which contains a program for reconstructing images. General block diagram of the system is shown in figure 2.1.To achieve our goals, we design our system using Proteus simulation and simulate two resistive phantoms, one for calibration and the other for simulating human tissue. Then the system is tested using these phantoms to calculate the accuracy of the system and reconstruct images for homogenous and non-homogenous tissues.

1.5 Thesis layout:

This thesis consists of five chapters, chapter one contains an introduction about EIT, chapter two contains literature review of previously designed EIT systems, chapter three contains the methodology that we follow to design the system, chapter four is results and discussions and chapter five is conclusion and recommendations. All codes used are written in appendices.

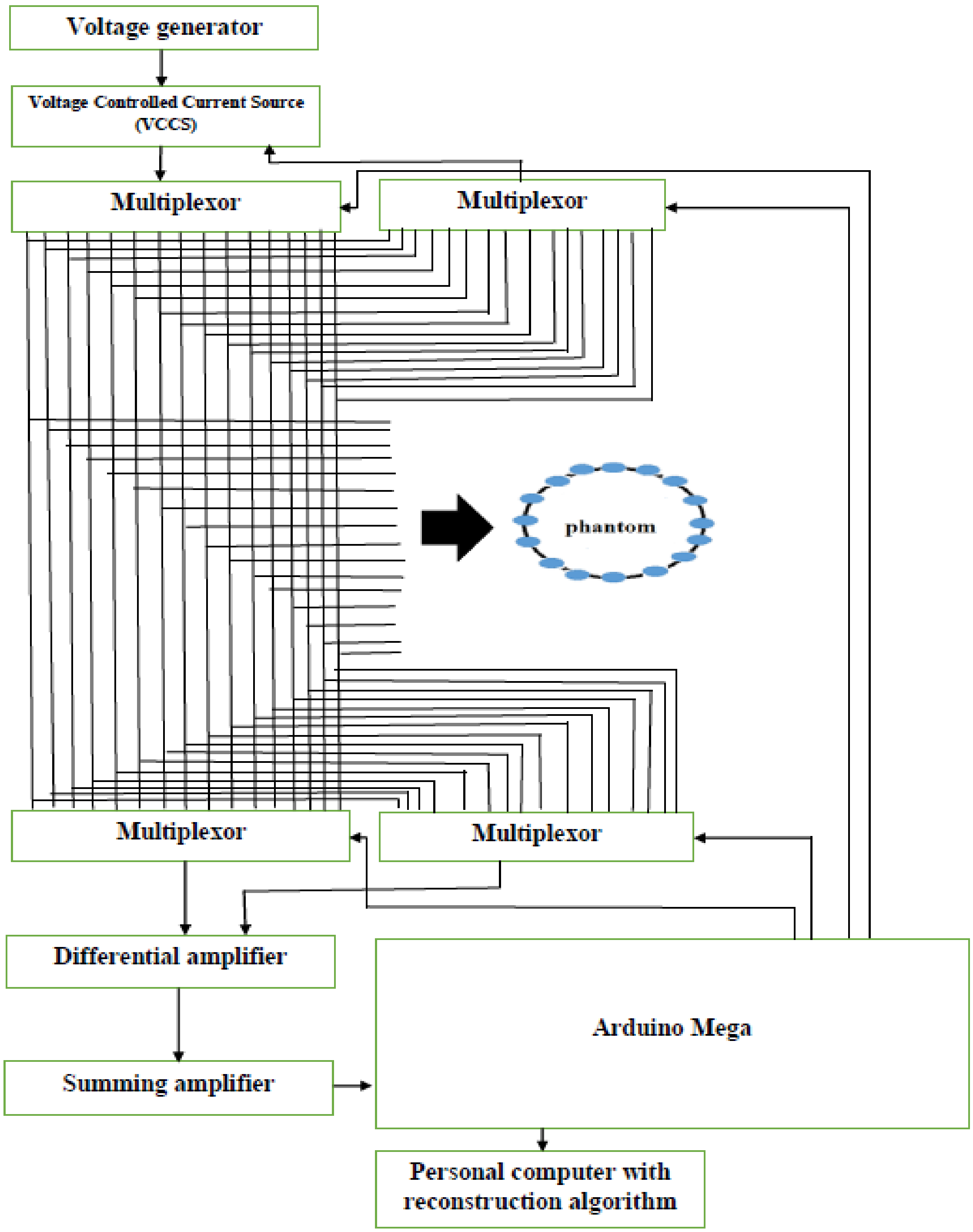


Figure1. 2: complete block diagram of the EIT system

CHAPTER TWO

LITERATURE REVIEW

CHAPTER TWO
LITERATURE REVIEW

Several electrical impedance tomographic systems have been developed over the years: fixed EIT systems, fixed EIT systems with handheld probe geometry and a portable and autonomous EIT IC system.

A bed type 3D EIT system for breast cancer detection was designed by V Cherepenin and others (2000); the system consists of compact array of 256 electrodes which supported on a rigid square plane, from which each electrode protrudes. Two additional electrodes are placed remotely from the array of electrodes. The system includes an output multiplexor which is connected to the electrode array and is the means by which an alternating current (AC) source is connected to one of the electrodes in the array. An input multiplexor connects one of the remaining electrodes of the array to a potential difference measuring unit. A microprocessor in the 3D EIT system and computer determine which electrode is selected for potential difference measurements (Cherepenin, 2000).

The second device (T-Scan technology) designed by Assenheimer and others (March 2001) is similar to the previous device (also used for breast cancer detection) but it does not produce tomographic reconstructions, it just maps the surface impedance using 256 electrodes (Assenheimer*et al.*, 2001).

A tiny modification in the previous design was done by Vladimir A. and others (2002), they introduce a system which consists of 256 electrodes array that are arranged in a round matrix. This system has a current source which consists of a microprocessor controlled digital to analog (D/A) convertor and 256 channel analog multiplexor that switches a single lead from current source to activate a single electrode in the electrode array. The potential difference detector consists of an integral instrumentation amplifier with a controlled gain factor, a passive low pass filter, analog to digital converter and the embedded software for digital signal processing (Vladimir *et al.*, 2002).

Soleimani (2006) showed low-cost equipment for reconstruction in 2 dimensions. The signal is digitally generated, using an EPROM (27C258) to storage a sinusoidal of 23 kHz. A counter reads the data from the EPROM and feeds a DAC (DAC-0808 National Semiconductor). This signal is fed to a buffer which in turn is connected to a Voltage

Controlled Current Source (VCCS) , performed with the operational AD644 (Analog Devices). For measuring the voltage, synchronous demodulator is used due to its ability to remove noise. It uses the AD625 instrumentation amplifier (Analog Devices) as the input stage before the acquisition card PCL-812PG I/O (Manuchehr, 2006)

Xu et al. created a system (2007) using 128 electrodes for three-dimensional images of the human thorax. Current is injected using the IC AD9852 (Analog Devices). The control module is implemented with the chip TMS320F2812 (Texas Instruments). The multiplexer MAX306 (Maxim) is used. For the acquisition of data the integrated AD624 (Analog Devices) is used as a pre-amplifier, then a fourth-order Butterworth filter is implemented with the integrated MAX275 (Maxim). The synchronizing signal is taken from the AD9852, and a synchronous demodulator is implemented in the DSP (Xu G*et al.*, 2007).

An EIT device was developed at Dartmouth College by Halter RJ (February 2008) for breast cancer detection, this device has 64 Ag/Agcl electrodes incorporated into a mechanical framework optimized for breast imaging and can be divided into three subsystems: a user interface computer, intermediate control module and a set of measurement channels. The control module services 64 channels configured on 16 separate circuit boards each of which provide signal generation and data acquisition. Both control and channel modules are designed around 32 bit digital signal processor (DSP) and field programmable gate arrays (FPGA). The communication between the three electronic subsystems is done via standard serial port interface (SPI) (Halter, 2008).

In contrast, an EIT system for breast cancer detection designed at Duke University by Ye G. (2008) has a 3D applicator with 128 electrodes on a cone-shaped surface; this applicator is attached to a switching network through which the AC voltage from function generator passes. The switching circuit consists of two parts (one for current driven and the other for voltage measurement); both are formed by two 64:1 multiplexors. The switching network is controlled by a computer via a digital input/output (DIO) card (Ye, 2008). Also Sussex EIM Mk4 system designed by Sze (2012) is very similar, the only difference being that the array of 85 electrodes is planar, this system based on National Instruments (NI) system which consists of a digitizer and a multifunctional data acquisition card (DAQ) (Sze, 2012).

Bera and Nagaraju developed (2009) a system that consists of a voltage controlled oscillator (VCO), VCO is used for current injection which is built with the MAX038 that feeds a modified Howland type current source. For voltage measurements a differential amplifier stage and a filter is used .Then the resulting voltage signal is measured with a multimeter and a digital oscilloscope (Bera and Nagaraju ,2009).

Matthew S. Campisi and others (2014) introduce a High-Density Flexible Electrode Arrays and Electrical Impedance Tomography system for breast cancer detection, this system uses a high density flexible micro-electrode arrays connected to a multiplexing head stage printed circuit board allowing high resolution data acquisition from 61 micro-electrodes. The stimulation hardware consists of Howland constant current source coupled to four 32:1 multiplexors. Electrode potential were buffered using Opamps (OPA2209, Texas instruments) and the actual current delivered to the electrode was measured using 50 Ohm resistor in series with each constant current source output. The potential across the resistor was measured using instrumentation amplifier. Voltages were sampled using 18 bit analog to digital converter (USB-6289, National Instrument). Sinusoidal stimulation signal were generated using 16 bit digital to analog converter integrated in the same DAQ system (USB-6289, National Instrument) (Matthew, 2014).

In all the aforementioned bed type and probe type systems, the electronic circuitry is contained in a big box, and a PC is used as the imaging device. But Sunjoo Hong come with more powerful study and high resolution device in which he designs a 4.9 mΩ-Sensitivity Mobile Electrical Impedance Tomography IC for Early Breast-Cancer Detection System (2014), it is a wearable device (brassiere) with 92 flexible electrode, the IC consists of four functional blocks: a switching network for reconfigurable measurement modes; Differential Sinusoidal Current Stimulator (DSCS) to inject the programmable single-tone current signal; 6 channel analog front-end to measure voltages with high sensitivity and perform digitization; and digital controller for system control and data calibration. The breast EIT image can be reconstructed and displayed on a portable smart device so that the user can get images easily at home (Sunjoo, 2014).

In Indian Institute of Science, Bangalore Tushar Kanti Bera and J. Nagaraju (2011) introduce a LabVIEW Based Electrical Impedance Tomography (EIT) System for Radiation Free Medical Imaging; it is a 16 electrode EIT system which three parts: EIT sensors or electrodes, electronic instrumentation and a personal computer (PC) with reconstruction algorithm. Electronic instrumentation consists of a constant current injector (CCI), electrode switching module (ESM), signal conditioner block (SCB) and a USB based data acquisition system (DAS). CCI is made up of a Voltage Controlled Oscillator (VCO) feeding the voltage signal to a voltage controlled current source (VCCS). VCO is developed with a MAX038 IC (Maxim Inc. USA) IC and it generates a sinusoidal signal feeding to VCCS. VCCS is basically a modified Howland constant current generator developed with AD829 ICs (Analog Devices Inc.). The automatic ESM is developed with four 16-channel CMOS analog multiplexers (MUX) controlled by the digital bits generated by the D/O ports of the DAS. DAS is developed with a NIUSB6251 data acquisition card (DAQ) controlled by a data acquisition program written in LabVIEW 8.2 software (Bangalore and Nagaraju , 2011).

Achmad Ansory and others introduce a system (2018) that consists of 32 electrodes which are connected to the four 32:1 multiplexers (ADG731BSUZ); two for the current injection and the other two for the boundary voltage measurement. Direct Digital Synthesis (DDS) AD9850 module is used for signal generation from and the current source is generated via a Voltage-Controlled Current Source (VCCS), namely Modified Howland Current Source. The output voltage is amplified first by AD8421 instrumentation amplifier. The voltage signal from the instrumentation amplifier is filtered by band pass filter. After filtering, the signal is then amplified again with the inverting amplifier based on AD8221; this amplifier optimizes the signal output voltage to approximately 5 V. The amplified signal is in sinusoidal form and hence only needed to measure its peak voltage or its root mean square (RMS) voltage. A peak detector that is designed based on AD8022 detects the peak of the sinusoidal signal and converts the sinusoidal signal to the DC signal. The peak voltage is then filtered by low pass filter based on OP97 Analog Device to reduce the ripple of the signal. To measure the peak voltage, ADC ADS1115 from Texas Instrument is used and configured to operate with differential mode input and its output is fed to the microcontroller which is used for controlling multiplexer, signal generator, Analog to Digital Converter (ADC) and sends boundary voltage data to the PC via a Universal Serial Bus (USB) cable (Achmad*et al.*, 2018).

All of these systems (from 2000 to 2018) shows that there are two feasible options for the EIT hardware, one option corresponding to a completely analog signal processing and the other option uses a digital signal processor. Eduardo Santos and Franco Simini (2012) introduce a review paper that shows "EIT systems which were designed based on analog signal processing using microprocessor, microcontroller…etc. have lowcost,difficult and complex design (the use of data acquisition system (DAQ) increase the cost of the EIT system), also designing systems using digital signal processors (DSP) make it difficult to achieve a truly compatible and harmonious system" (Eduardo and Franco, 2012) Here we design an EIT system based on analog signal processing using Arduino, the goal is to have a simple and low cost EIT system and make benefits of the Arduino characteristics compared with microprocessor and microcontroller.

CHAPTER THREE
METHODOLOGY

CHAPTER THREE
METHODOLOGY

3.1 Electrical Impedance Tomography System:

In this research, Proteus based 16 electrode EIT system for radiation free medical imaging has been developed which injects a low amplitude low frequency AC current to the subject (represented using resistive phantom) and surface potentials are acquired to reconstruct its tomographic image.

Our EIT system has two main parts; the first part is responsible for injecting current and acquiring potentials while the second part is responsible for reconstructing the tomographic image.

The sinusoidal current which is generated using an AC voltage generator and Voltage Controlled Current Source (VCCS) is injected into an automatic electrode switching module (ESM) which is developed with four high speedComplementary Metal Oxide Semiconductor (CMOS) analogue multiplexers called CD4067B ICs.Two of these multiplexors are used for injecting the current to the first adjacent pair of electrodes while the othersare used to acquire voltage potentials from the rest adjacent pairs of electrodes. The switching of either current injection or voltage potentials measurement is done automatically using the multiplexors that are interfaced with the Arduino microcontroller by a program developed to control the multiplexors operation.

In order to get the difference in voltage between the adjacent pair of electrodes, the acquired voltages are transferred to a differential amplifier which resulted in a value that is transferred to a summing amplifier to make it suitable to be read by the Arduino microcontroller. This process repeats itself until it achieves (13 x 16) = (208) sets of voltage measurements.

Finally, this data is fed into Excel sheet using Virtual Serial Port Emulator (VSPE) and PLX-DAQ-v2.11 and then executed in MATLAB which is interfaced with EIDORS (Electrical Impedance and Diffuse Optical Tomography Reconstruction Software which is a program introduced by EIT research) software to reconstruct the image based on the data acquired. The complete block diagram of the working system is shown in Figure 2.1.

3.2 Electrode current Source:

Using Proteus, the current source is implemented by using a voltage source and preexist VCCS package. The VCCS importance comes from its ability to maintain the stability of the current at a certain load range. This circuit serves to set the electrical current generated to be always constant when load is given.

Ac Voltage source with a value (5m v, 50 Hz) is fed to the VCCS package which has a unity gain; the VCCS gives an output current of about (5 m A, 50 Hz).the circuit diagram is shown in figure 3.1.

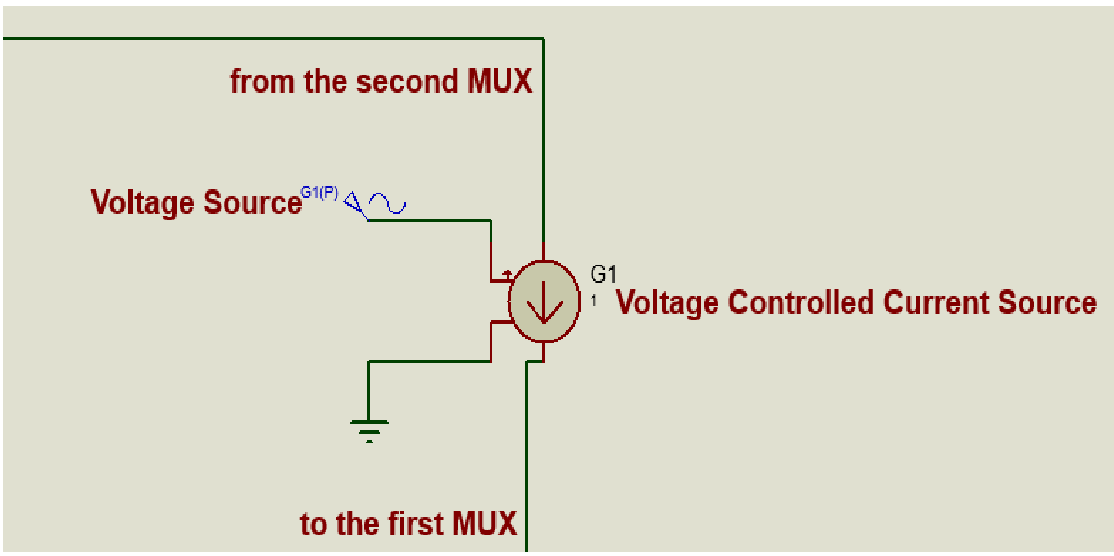


Figure 3. 1: Voltage source and Voltage Controlled Current Source

Original systems use relatively low frequency excitation (10-20KHz) while newer systems apply waveform up to (1-10 MHz) with maximum peak current values in the range (0.1-5 mA).The reason for using high frequency signal is that human cell acts like capacitor making it possible for current to pass through the system when current frequency is high.

In the proposed system we use current with amplitude 5mA which lies in the acceptable safe range for the patient while the frequency is only 50 Hz (we use a resistive phantom which is not affected by the value of frequency). Also the reason for using low frequency current is due to the limitations accompanying with Proteus software as it takes a lot of time to process any circuit with high frequency current and this lead to terminating the execution due to excessive load on the CPU.

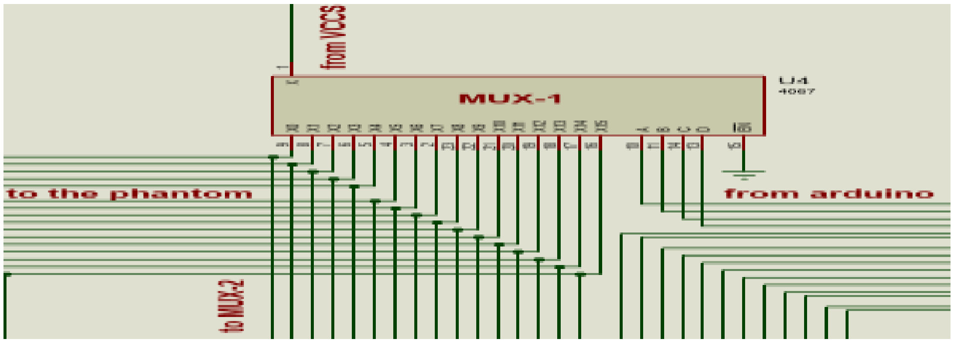
3.3 Automatic Electrode Switching Module (ESM):

Automatic Electrode Switching Module (ESM) is developed with four high speed Complementary Metal Oxide Semiconductor (CMOS) 1:16 analogue multiplexers called CD4067B ICs. Two of these multiplexors (MUX-1 and MUX-2) are used for switching the current injection between adjacent pair of electrodes while the other multiplexors (MUX-3 and MUX-4) are used for switching the voltage potential measurements between the rest pairs of adjacent electrodes. The circuit diagram of ESM is shown in figure 3.2.

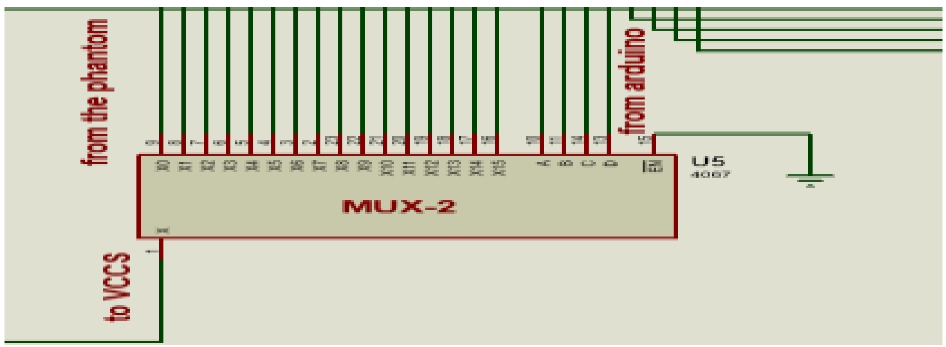
The digital bits required to control the operation of each multiplexor to switch the current injection and voltage potential measurements are generated by Arduino microcontroller. Each multiplexor requires four digital bits. Here, 16-bit parallel digital data are generated using Arduino microcontroller and a program is written to convert it to 16-bit parallel digital data required for automatic switching of the current injection and voltage measurements for the surface electrodes of 16 electrode EIT system.

The VCCS injects its output current to MUX-1 which is enabled by the Arduino to fed the current to electrode-1 (electrode-1, electrode-2…electrode-16 are attached to the surface of the phantom). Then current pass through (electrode-2) which is enabled by MUX-2. To complete the circuit of current injection, MUX-2 is connected to the ground of the VCCS. The same process is done for voltage potentials measurements using MUX-3 and MUX-4 to acquire voltages from the rest adjacent electrodes. This process repeated until it achieves (13 x 16) = (208) sets of voltage measurements.as shown in figure 3.3.

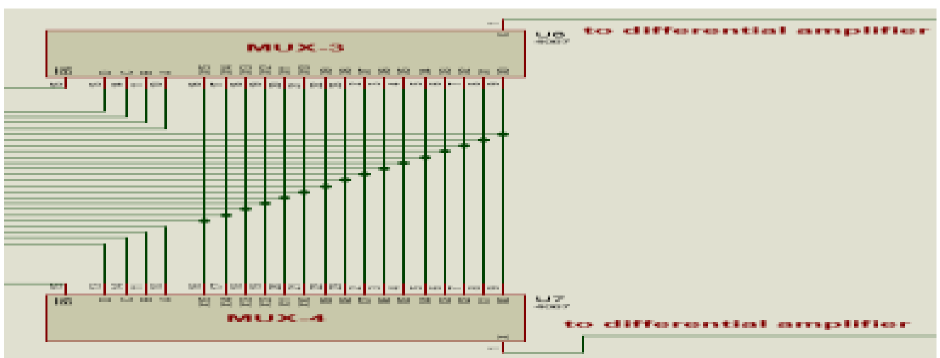
The switching sequence of the output digital pins from the Arduino and the corresponding channel of the multiplexers for the first , second and third current injection are shown in table 3.2.



(a)



(b)



(c)

Figure 3. 2: Current and Voltage Switching Module (a) MUX-1 (b) MUX-2 (c) MUX-3 and MUX-4

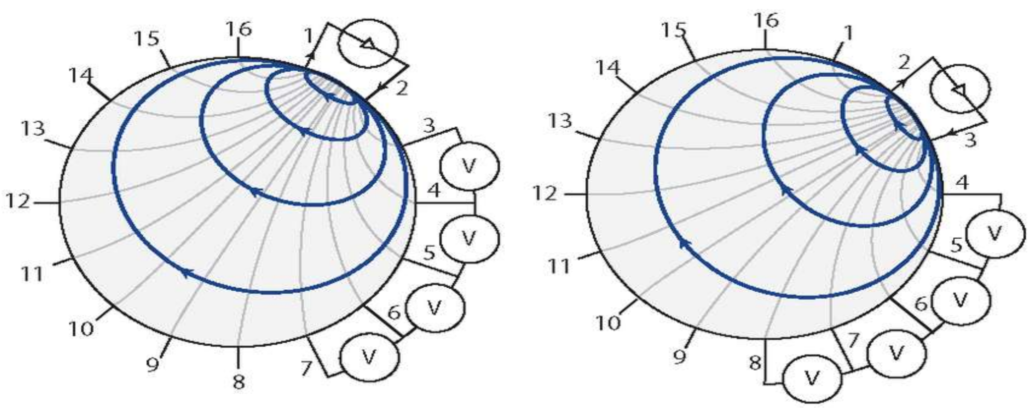


Figure 3. 3: Sequence of measurements performed in EIT system

Table 3. 1: The switching sequence of the output digital pins from the Arduino and the corresponding channel of the multiplexers for the first, second and third current

	MUX-1	MUX-2	MUX-3	MUX-4
	D C B A	D C B A	D C B A	D C B A
1	0 0 0 0	0 0 0 1	0 0 1 0	0 0 1 1
			0 0 1 1	0 1 0 0
			0 1 0 0	0 1 0 1
			0 1 0 1	0 1 1 0
			0 1 1 0	0 1 1 1
			0 1 1 1	1 0 0 0
			1 0 0 0	1 0 0 1
			1 0 0 1	1 0 1 0
			1 0 1 0	1 0 1 1
			1 0 1 1	1 1 0 0
			1 1 0 0	1 1 0 1
			1 1 0 1	1 1 1 0
			1 1 1 0	1 1 1 1
2	0 0 0 1	0 0 1 0	0 0 1 1	0 1 0 0
			0 1 0 0	0 1 0 1
			0 1 0 1	0 1 1 0
			0 1 1 0	0 1 1 1
			0 1 1 1	1 0 0 0
			1 0 0 0	1 0 0 1
			1 0 0 1	1 0 1 0
			1 0 1 0	1 0 1 1
			1 0 1 1	1 1 0 0
			1 1 0 0	1 1 0 1
			1 1 0 1	1 1 1 0
			1 1 1 0	1 1 1 1
			1 1 1 1	0 0 0 0

3	0 0 1 0	0 0 1 1	0 1 0 0	0 1 0 1
			0 1 0 1	0 1 1 0
			0 1 1 0	0 1 1 1
			0 1 1 1	1 0 0 0
			1 0 0 0	1 0 0 1
			1 0 0 1	1 0 1 0
			1 0 1 0	1 0 1 1
			1 0 1 1	1 1 0 0
			1 1 0 0	1 1 0 1
			1 1 0 1	1 1 1 0
			1 1 1 0	1 1 1 1
			1 1 1 1	0 0 0 0
			0 0 0 0	0 0 0 1

3.4 Phantoms:

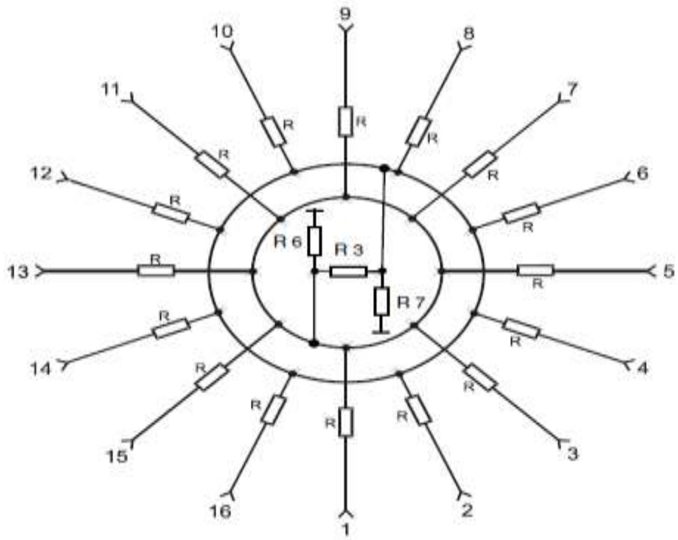
The current injected by VCCS through MUX-1 and MUX-2 is fed to the phantom (through 16 electrodes) and the corresponding voltage potentials are read by the arduino through MUX-3 and MUX-4. Here two phantoms are used; Calibration and Cardiff phantom.

3.4.1 Calibration phantom:

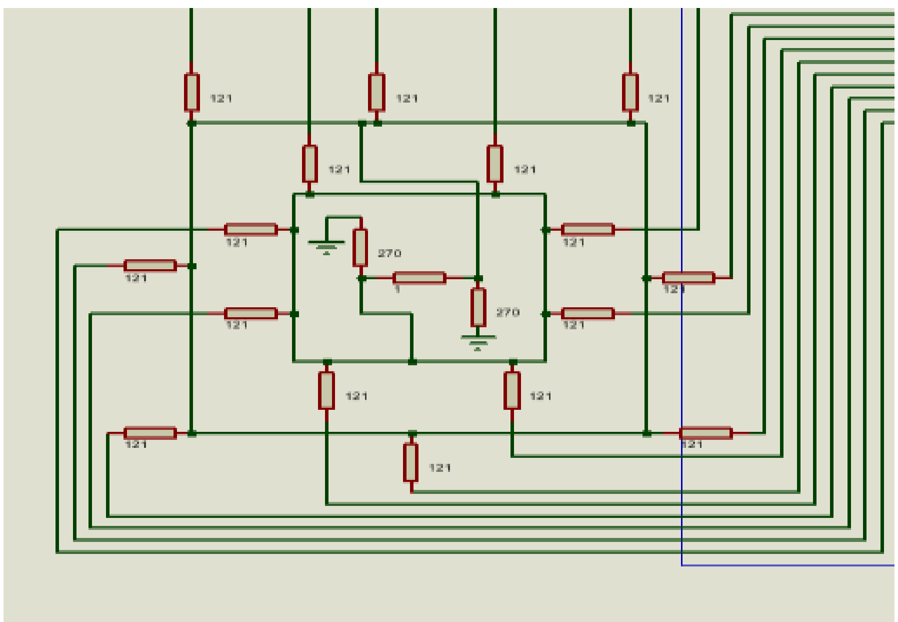
is a simple phantom to determine systematic errors that will occur in the measurements by EIT systems. It is a simple scalable resistive phantom (composed of 1Ω, 121 Ω and 270Ω resistors) [7] using a 16 electrode adjacent drive pattern. The output voltage of the phantom is constant for all combinations of current injection and voltage measurements because it depends only on the resistor (1Ω), so the output voltage (v) is given by:

$$V = \text{input current} * 1\Omega$$

Figure 3.4 shows the circuit diagram of the calibration phantom with electrodes represented by numbers from 1 to 16.



(a)



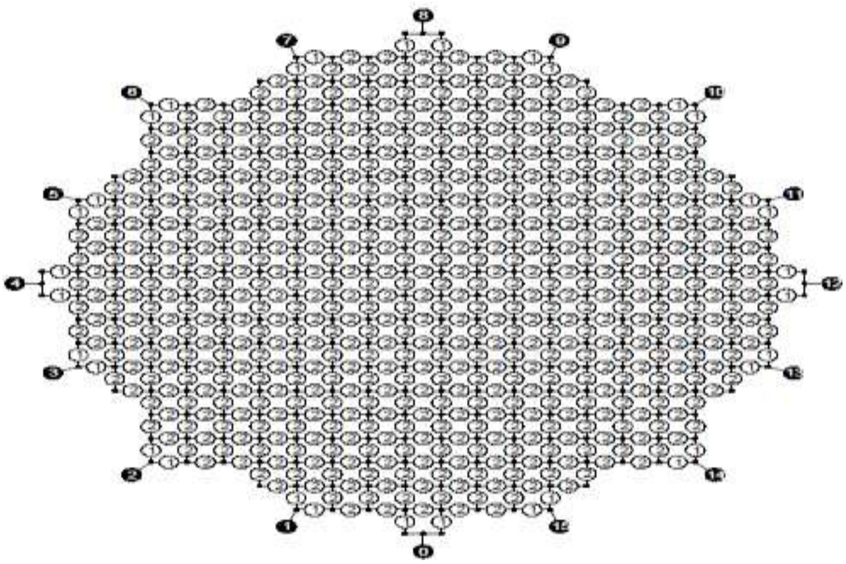
(b)

Figure 3. 4

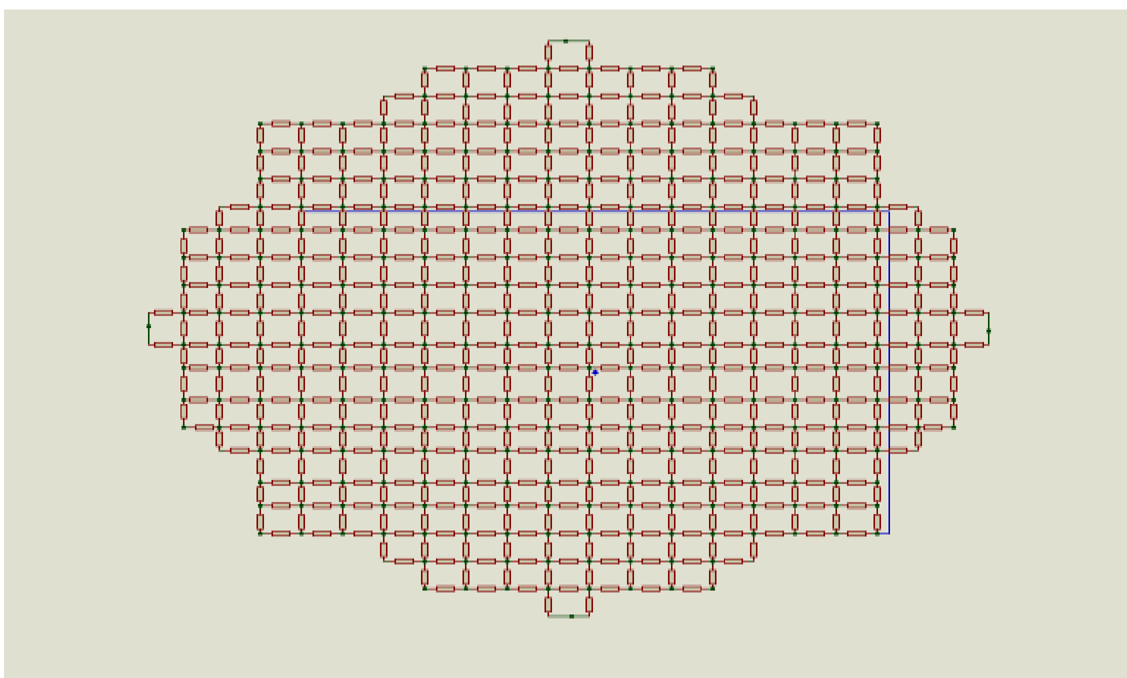
Figure 3. 4:calibration phantom (a) Circuit diagram of calibration phantom. (b) Proteus simulation of calibration phantom

3.4.2 Cardiff phantom:

This phantom composed of a mesh of 51 Ω and 100 Ω resistors. As shown in figure 3.5. The black circles represent the position of the 16 electrodes (Griffiths, 1988).



(a)



(b)

Figure 3. 5: Cardiff phantom (a) Circuit diagram of Cardiff phantom(b) Proteus simulation of Cardiff phantom

This phantom able to simulate different body tissues, changes in the apparent electrical conductivity can be introduced at a particular location within the phantom by shunting the resistors in the mesh with additional resistors. To increase the electrical conductivity by a factor (m) in four pixels, the required components are resistors (R') and (R"), where

$$R' = \frac{R}{(m-1)} \text{..........}(1)$$

$$R" = R\frac{(m+1)}{(m-1)} \text{.........}(2)$$

(R)is the value of the resistors in the main mesh. The conductivity can be increased by the same factor over a larger region by using values (R') everywhere in the interior and (R")on the periphery ((Griffiths, 1988)as shown in figure 3.6.

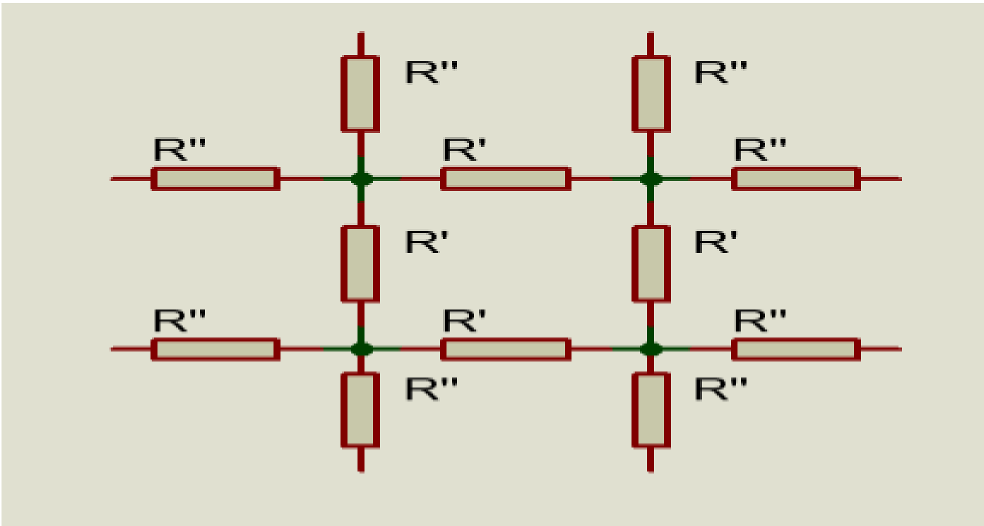


Figure 3. 6: required Components to increase conductivity

To increase the conductivity in our phantom by a factor m=2 ,R' and $R"$should equal to**:**

$$R' = \frac{R}{(m-1)} = \frac{100}{(2-1)} = 100\Omega$$

$$R" = R\frac{(m+1)}{(m-1)} = 100\frac{(2+1)}{(2-1)} = 300\Omega$$

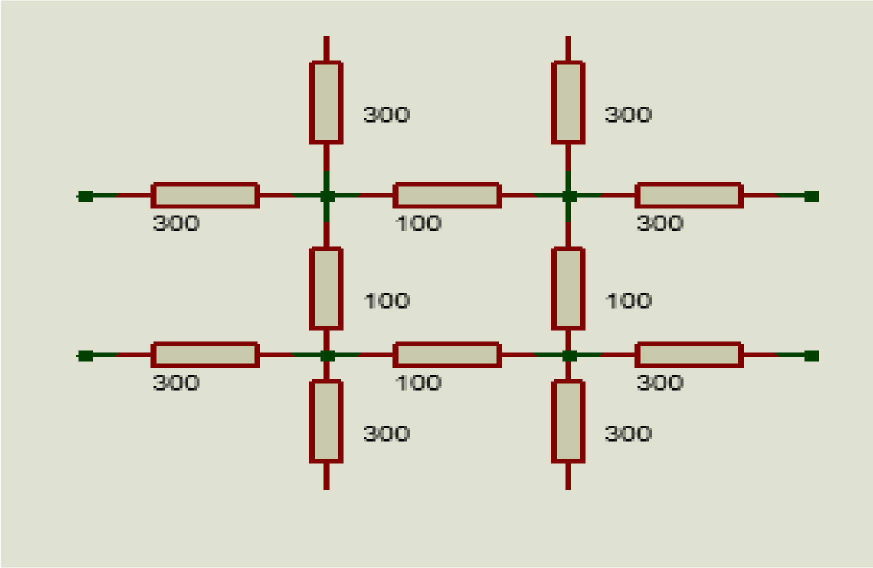


Figure 3. 7: required Components to increase conductivity by a factor m =2

3.5 Differential amplifier:

In order to reconstruct the image, the difference in voltage between two adjacent electrodes is needed; this difference can be achieved using differential amplifier bytreating the MUX-3 output as an input for the negative input terminal of the differential amplifier while treating MUX-4 output as input for the positive input terminal of the differential amplifier.

The differential amplifier is designed with unity gain to give an output voltage equal to difference between voltages of two adjacent electrodes as shown below:

$$\text{Output Voltage} = \frac{\text{feedback resistor}}{\text{input resistor}}(V_2 - V_1)$$

$$= \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega}(V_2 - V_1) = (V_2 - V_1)$$

Where V_2 is the voltage value at the positive amplifierterminal (from the first electrode)and V_1 is the voltage value at the negative amplifier terminal (from the second electrode).

The circuit diagram of the differential amplifier is shown in figure 3.8.

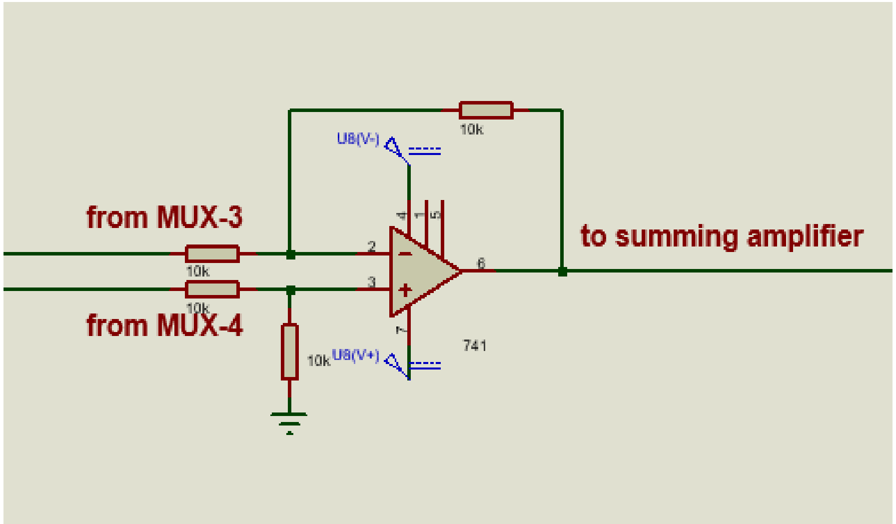


Figure 3. 8:Differential Amplifier

3.6 Summing Amplifier:

Summing amplifier provide an input that is suitable to be read by Arduino, the Arduino could read positive analogue values in the range from 0 to 5V. So the summing amplifier used here (with gain=1) could add a DC offset with value 2.5 volt for each input resulting in positive values in the range from 0 to 5V.the circuit diagram of the summing amplifier is shown in figure 3.9.

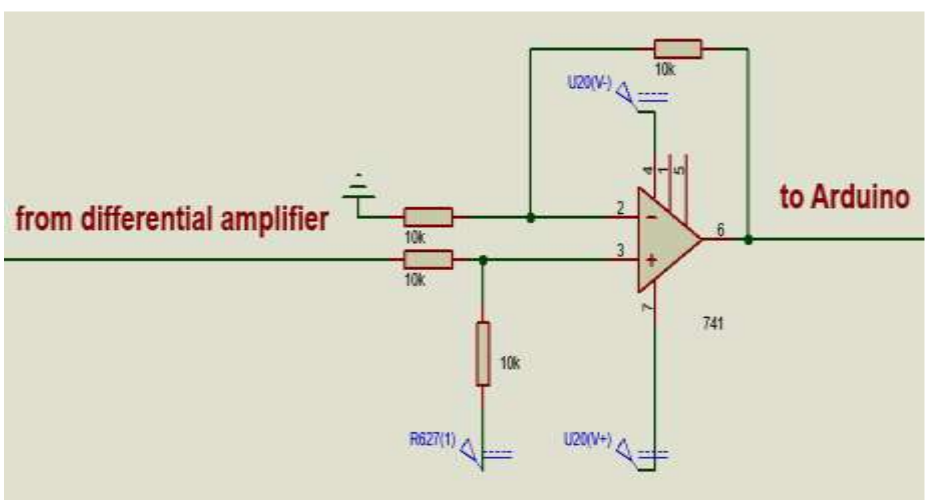


Figure 3. 9: Summing Amplifier

For our non-inverting summing amplifier:

$$\text{Output Voltage} = \left(1 + \frac{\text{feedback resistor}}{\text{input resistor}}\right)\left(V_2 \frac{R_2}{R_2 + R_1} + V_1 \frac{R_1}{R_2 + R_1}\right)$$

$$= \left(1 + \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega}\right)\left(input\ voltage \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 10\ \text{k}\Omega} + 2.5 \frac{10\ \text{k}\Omega}{10\ \text{k}\Omega + 10\ \text{k}\Omega}\right)$$

$$= (input\ voltage + 2.5V)$$

Where R_1 is the input resistor of first voltage input (from differential amplifier) and R_2 is the input resistor of 2.5 V input

3.7 Arduino:

There are two ways found in the literature, for controlling any EIT system:

(1) Analog signal processing:It involvesthe use of microprocessor or microcontroller for controlling and synchronization of different blocks (require the use of discrete components which increase the difficulty and complexity of the design).Also data acquisition card can be used, these cards would provide the A/D and communication with the computer and have multiple input channels, making it possible to have a channel for each pair of electrodes, enabling measure in parallel, this also means build 16 input channels, increasing the cost (minimum cost 690$) and difficulty of design.

(2) Digital signal processing:It involves the use of digital signal processors (DSP) which increase the cost of the system and makes it difficult to achieve a truly compatible and harmonious system.

The control process in our EIT system is based on analog signal processing using Arduino. The use of Arduino instead of microprocessor, microcontroller or DSPs could offer some advantages to the system as it owns the many characteristics such as Compact (build in ADC, LEDs…etc.), Inexpensive (Arduino compact package costs only 5.88$)., Cross-platform (The Arduino Software (IDE) runs on Windows, Macintosh OSX, and Linux operating systems),Simple, clear programming environment, has Open source and extensible software and has Open source and extensible hardware.

Here we use Arduino Mega1280, it is a microcontroller board based on ATmega1280and has 54 digital input/output pins, 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, USB connection and reset button.as shown in figure 3.10.

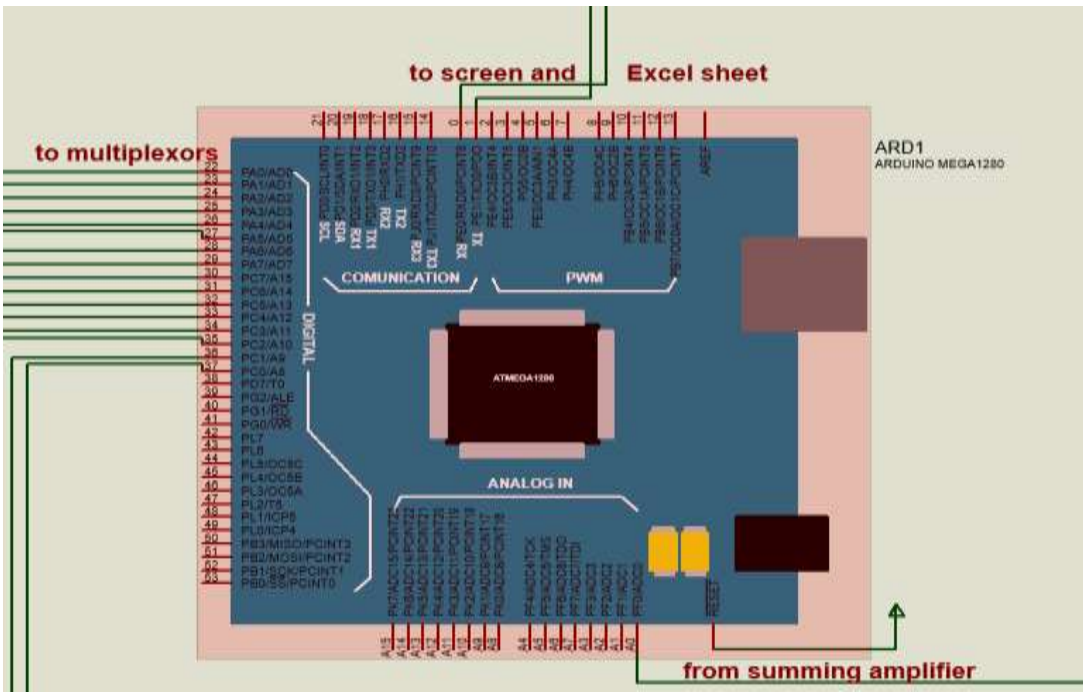


Figure 3. 10: Arduino Mega1280

It used to:

(1) Control the four multiplexors operations using 16 digital pin (from 22 to 37):

In Arduino, pins number (22, 23, 24 and 25) are used to control MUX-1, pins number (26, 27, 28 and 29) are used to control MUX-2,pins number (30, 31, 32and 33) are used to control MUX- 4 and pins number (34, 35, 36 and 37) are used to control MUX-3. This control is performed to injects the current and read the voltages according to adjacent sequences as shown in table 3.2.

(2) Read the analog outputs of the summing amplifier using analog pin (A0):

Using analogRead( ) command in the Arduino at pin (A0) enables reading of the output voltage from the summing amplifier in the range from 0 to 5 V.

(3) Find the Root Mean Square (RMS):

As the output voltage from the summing amplifier is an AC voltage, RMS value should be calculated and this is done using special commands in Arduino.
The output voltage has a frequency of about 50 Hz, so period time (T) is equal to:

$$T= \frac{1}{50\ \text{Hz}} = 0.02\ \text{second} = 20\ \text{millisecond}$$

In order to get RMS value close to (Voltage peak value /√2) we take 40 samples (from 2 periods) by taking one sample every 1 millisecond (using 500 instances).

(4) Print the resultson a virtual screen using (TX) and (RX) pin:

TX and RX are transmit and receive pins in Arduino, they are used to send the voltages values to the virtual screen in Proteus by connecting them to RXD and TXD pins in the virtual screen.

(5) Save the results in Excel sheet using (TX) and (RX) pin:

Also RX and TX are connected to the port (COM1) to make it possible to transmit the voltages values to an Excel sheet.
In order to make Arduino execute these 5 tasks, a code is written and loaded in it (Appendix A: Arduino code for the first, second and third current injection).

3.8 Virtual screen and Port (COM1):

The 208 data from Arduino is received by the virtual screen to display it. Also this data is transmitted to an Excel sheet (PLX-DAQ-v2.11) using the port (COM1) and theVirtual Serial Port Emulator (VSPE). VSPE is software that makes a virtual connection between the Proteus (COM1) and the Excel sheet.In PLX-DAQ-v2.11 Excel sheet, VSPE and

Proteus, the port (COM1) is specified. Figure 3.11 shows the virtual screen and the port (COM1) in Proteus.

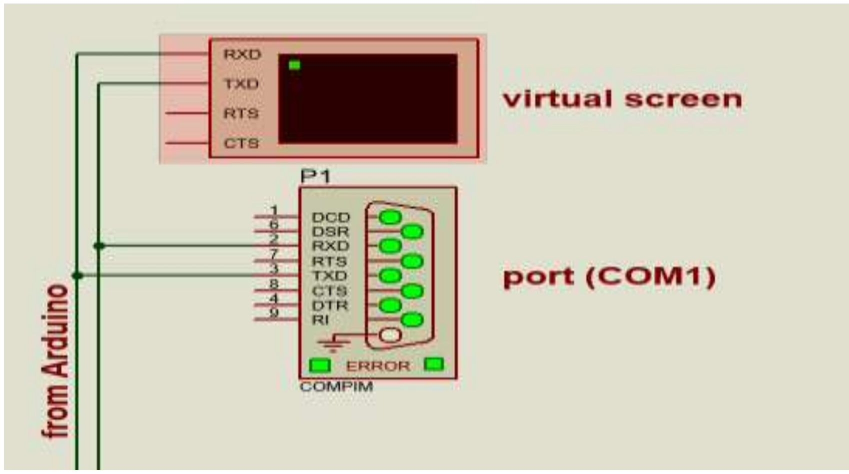


Figure 3. 11: the virtual screen and the port (COM1)

3.9 Reconstruction using EIDORS:

EIDORS (Electrical Impedance and Diffuse Optical Tomography Reconstruction Software) is a specialized MatLab toolbox for image reconstruction using electrical impedance values obtained from a specific sequence of connection over an array of electrodes. The EIDORS action is shown in figure 3.12.

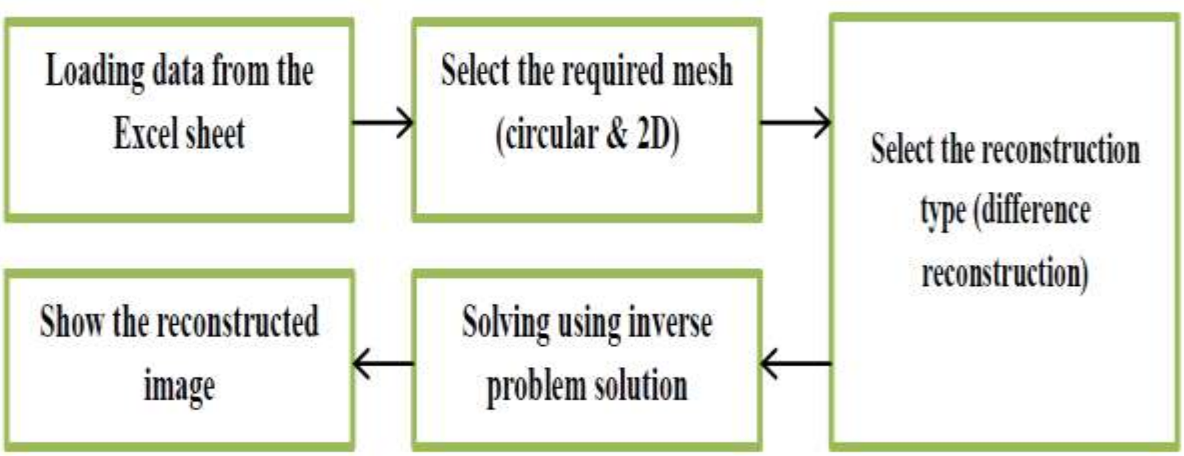


Figure 3. 12: Block diagram for EIDORS action

The application of this action is done through a code that is specified in Appendix (B). Line 8 of the program:

```
imdl.fwd_model.stimulation=
mk_stim_patterns(16,1,[1,0],[0,1],{'no_meas_current'},5);
```

refers the main configuration of sequences for currentapplication and voltage measurements. The format of theinstruction parameters are described as:

“16” sixteen electrodes.

“1” one ring with a set of 16 electrodes.

“[1, 0]” polarity of the current supply; a”1” means positivefor the first electrode and “0” negative for the second,considering a pair of electrodes. Sequence of selection ofelectrodes is clockwise.

“[0, 1]” polarity of the voltage measurement; a “0” meansnegative for the first electrode and “1” positive for thesecond, considering a pair of electrodes. Sequence ofselection of electrodes is clockwise.

“5 “current value of 5 mA.

The overall circuit is shown in figure 3.13, Cardiff phantom is used here to represent human tissue and it is attached to the system through 16 electrodes which are represented here by wires.

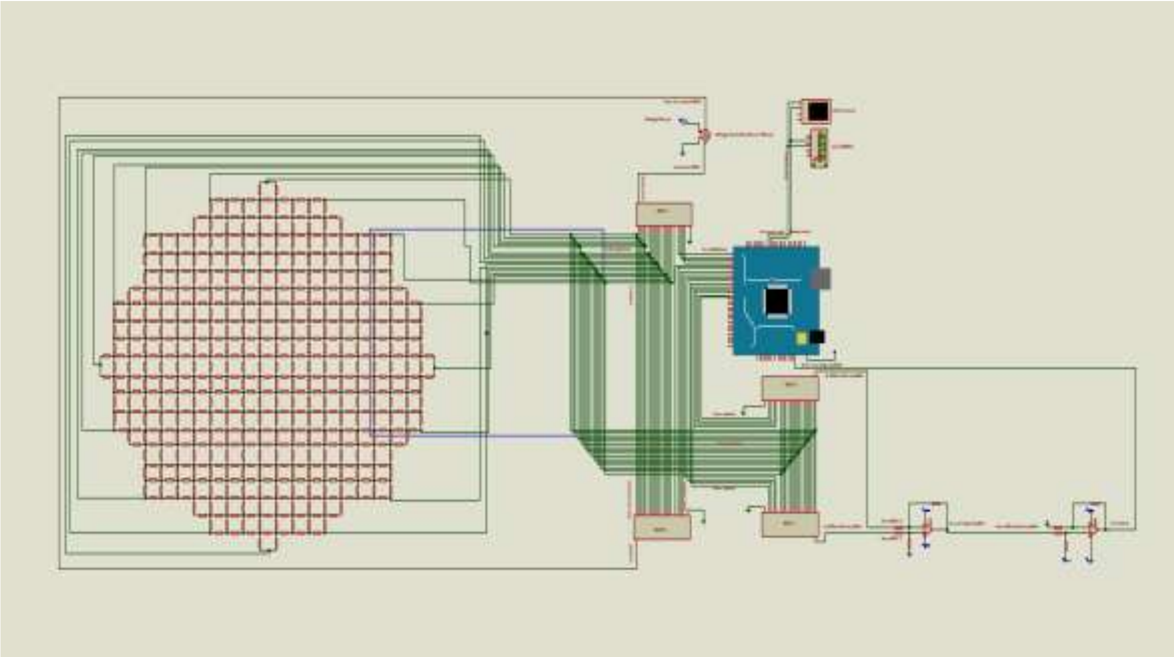


Figure 3. 13: The overall EIT system

CHAPTER FOUR

RESULTS AND DISCUSSIONS

CHAPTER FOUR
RESULTS AND DISCUSSIONS

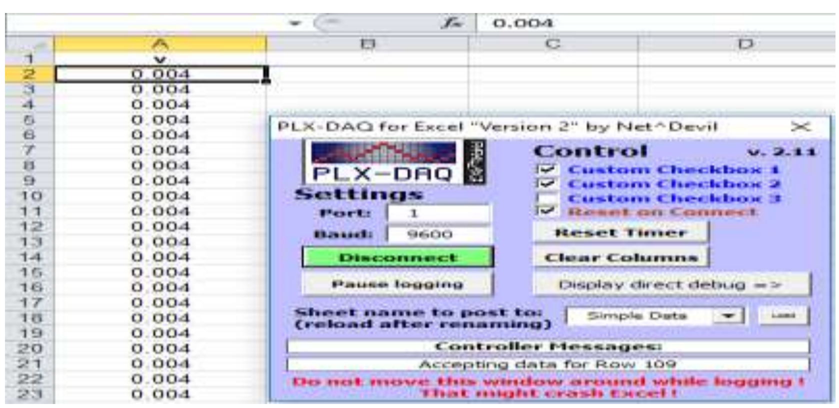
4.1 Results:

The EIT circuit described in the previous chapter wasapplied using Proteus. The voltage measurements were recorded and saved in an Excel sheet using both calibration phantom and Cardiff phantom.

4.1.1 Use of calibration phantom:

When an AC current with a value (5m A) was injectedusing VCCS, all the 208 voltage measurements were identical with a value of (0.004 V) as shown in figure 4.1.

(a)



(b)

Figure 4. 1: Results of using calibration phantom in (a) virtual screen (b) Excel sheet

4.1.2 Use of Cardiff phantom:

To represent the background, An AC current with a value (5m A) was injected to a normal Cardiff phantom (with 100 Ω and 51Ω resistors) and the 208 voltage measurements were recorded in an excel sheet.

To represent a tissue with tumor (foreground), firstly, An AC current with a value (5m A) was injected to a Cardiff phantom (with changing resistors close to electrode-1 by a factor m=2 using equation (1) and (2)) and the 208 voltage measurements were recorded in an excel sheet with values shown in table 4.1.

Table 4. 1: Voltage measurements from 1 to 16 electrodes for tumor close to electrode-1

Electrode/cycle	1	2	3	4	5	6	7	8
0	x	x	0.024	0.007	0.005	0.007	0.005	0.003
1	x	x	x	0.024	0.014	0.014	0.009	0.004
2	0.025	x	x	x	0.039	0.025	0.014	0.006
3	0.007	0.023	x	x	x	0.039	0.014	0.004
4	0.005	0.014	0.039	x	x	x	0.024	0.007
5	0.007	0.014	0.026	0.039	x	x	x	0.024
6	0.005	0.009	0.014	0.014	0.024	x	x	x
7	0.003	0.004	0.006	0.004	0.007	0.024	x	x
8	0.003	0.004	0.004	0.004	0.004	0.014	0.039	x
9	0.004	0.007	0.007	0.004	0.006	0.014	0.026	0.039
10	0.006	0.007	0.007	0.004	0.004	0.009	0.014	0.014
11	0.004	0.004	0.004	0.003	0.003	0.004	0.006	0.004
12	0.006	0.006	0.004	0.003	0.003	0.004	0.004	0.004
13	0.016	0.014	0.009	0.004	0.004	0.007	0.007	0.004
14	0.05	0.028	0.014	0.006	0.004	0.007	0.007	0.004
15	x	0.05	0.016	0.006	0.004	0.006	0.004	0.003

9	10	11	12	13	14	15	16
0.003	0.004	0.006	0.004	0.006	0.016	0.05	x
0.004	0.007	0.007	0.004	0.005	0.014	0.028	0.05
0.004	0.007	0.007	0.004	0.004	0.009	0.014	0.016
0.004	0.004	0.004	0.003	0.003	0.004	0.006	0.006
0.004	0.006	0.004	0.003	0.003	0.004	0.004	0.004
0.014	0.014	0.009	0.004	0.004	0.007	0.007	0.006
0.039	0.026	0.014	0.006	0.004	0.007	0.007	0.004
x	0.039	0.014	0.004	0.004	0.004	0.004	0.003
x	x	0.024	0.007	0.004	0.006	0.004	0.003
x	x	x	0.024	0.014	0.014	0.009	0.005
0.024	x	x	x	0.039	0.026	0.014	0.007
0.007	0.024	x	x	x	0.039	0.014	0.005
0.004	0.014	0.039	x	x	x	0.024	0.007
0.006	0.014	0.026	0.039	x	x	x	0.025
0.004	0.009	0.014	0.014	0.024	x	x	x
0.003	0.005	0.007	0.005	0.007	0.025	x	x

For image reconstruction, the background and foreground data were simulated using EIDORS and the result is shown in figure 4.2.

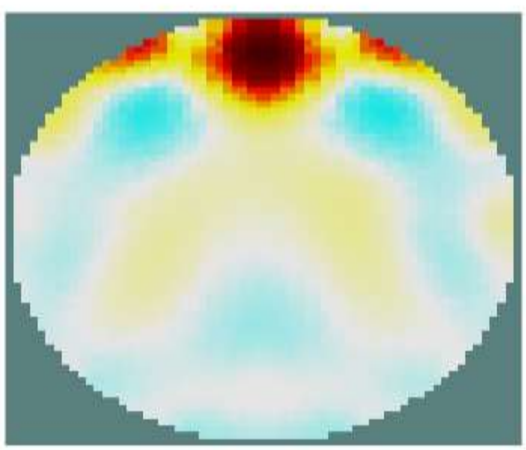


Figure 4. 2: Resistivity Image Created by EIDORS with tumor close to electrode-1

Secondly,An AC current with a value (5m A) was injected to a Cardiff phantom (with changing resistors in the middle between electrode-6 and the center of the phantom by a factor m=2 using equation (1) and (2)) and the 208 voltage measurements were recorded in an excel sheet with values shown in table 4.2.

.

Table 4. 2:Voltage measurements from 1 to 16 electrodes for tumor between electrode-6 and the center of the phantom

Electrode/cycle	1	2	3	4	5	6	7	8
0	x	x	0.024	0.007	0.004	0.006	0.004	0.003
1	x	x	x	0.024	0.014	0.014	0.01	0.004
2	0.024	x	x	x	0.039	0.026	0.015	0.007
3	0.007	0.024	x	x	x	0.039	0.014	0.005
4	0.004	0.014	0.039	x	x	x	0.024	0.007
5	0.006	0.014	0.026	0.039	x	x	x	0.024
6	0.004	0.01	0.015	0.014	0.024	x	x	x
7	0.003	0.004	0.006	0.005	0.007	0.024	x	x
8	0.003	0.004	0.005	0.004	0.005	0.014	0.039	x
9	0.004	0.007	0.007	0.005	0.006	0.015	0.026	0.039
10	0.004	0.007	0.007	0.004	0.004	0.01	0.014	0.014
11	0.004	0.004	0.004	0.003	0.003	0.004	0.006	0.004
12	0.004	0.006	0.004	0.003	0.003	0.004	0.005	0.004
13	0.014	0.014	0.009	0.004	0.004	0.007	0.007	0.004
14	0.039	0.026	0.014	0.006	0.004	0.007	0.007	0.004
15	x	0.039	0.014	0.004	0.004	0.005	0.004	0.003

9	10	11	12	13	14	15	16
0.003	0.004	0.004	0.004	0.004	0.014	0.039	x
0.004	0.007	0.007	0.004	0.006	0.014	0.026	0.039
0.005	0.007	0.007	0.004	0.004	0.009	0.014	0.014
0.004	0.005	0.004	0.003	0.003	0.004	0.006	0.004
0.005	0.006	0.004	0.003	0.003	0.004	0.004	0.004
0.015	0.015	0.01	0.004	0.004	0.007	0.007	0.005
0.039	0.026	0.014	0.006	0.005	0.007	0.007	0.004
x	0.039	0.014	0.004	0.004	0.004	0.004	0.003
x	x	0.024	0.007	0.004	0.006	0.004	0.003
x	x	x	0.024	0.014	0.014	0.009	0.004
0.024	x	x	x	0.039	0.026	0.014	0.006
0.007	0.024	x	x	x	0.024	0.014	0.004
0.004	0.014	0.039	x	x	x	0.024	0.007
0.006	0.014	0.026	0.039	x	x	x	0.024
0.004	0.009	0.014	0.014	0.024	x	x	x
0.003	0.004	0.006	0.004	0.007	0.024	x	x

For image reconstruction, these data were simulated using EIDORS and the result is shown in figure 4.3.

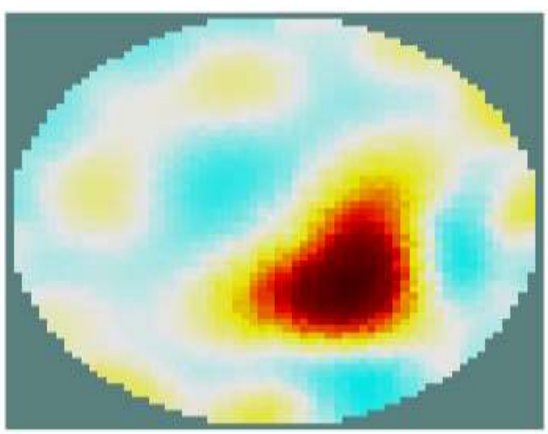


Figure 4. 3: Resistivity Image Created by EIDORS with tumor between electrode-6 and the center of the phantom

Finally,An AC current with a value (5m A) was injected to a Cardiff phantom (with changing resistors in the middle of the phantom by a factor m=2 using equation (1) and (2)) and the 208 voltage measurements were recorded in an excel sheet with values shown in table 4.3.

Table 4. 3: Voltage measurements from 1 to 16 electrodes for tumor in the middle of the phantom

Electrode/cycle	1	2	3	4	5	6	7	8
0	x	x	0.024	0.007	0.004	0.006	0.004	0.003
1	x	x	x	0.024	0.014	0.014	0.009	0.004
2	0.024	x	x	x	0.039	0.026	0.014	0.006
3	0.007	0.024	x	x	x	0.039	0.014	0.004
4	0.004	0.014	0.039	x	x	x	0.024	0.007
5	0.006	0.014	0.026	0.039	x	x	x	0.024
6	0.004	0.009	0.014	0.014	0.024	x	x	x
7	0.003	0.004	0.006	0.004	0.007	0.024	x	x
8	0.003	0.004	0.004	0.004	0.004	0.014	0.039	x
9	0.004	0.007	0.007	0.005	0.006	0.014	0.026	0.039
10	0.005	0.007	0.007	0.004	0.004	0.009	0.014	0.014
11	0.004	0.004	0.004	0.003	0.003	0.004	0.006	0.004
12	0.004	0.006	0.004	0.003	0.003	0.004	0.005	0.004
13	0.014	0.014	0.009	0.004	0.004	0.007	0.007	0.005
14	0.039	0.026	0.014	0.006	0.004	0.007	0.007	0.004
15	x	0.039	0.014	0.004	0.004	0.005	0.004	0.003

9	10	11	12	13	14	15	16
0.004	0.005	0.004	0.004	0.014	0.039	x	0.004
0.007	0.007	0.005	0.006	0.014	0.026	0.039	0.007
0.007	0.007	0.004	0.004	0.009	0.014	0.014	0.007
0.005	0.004	0.003	0.003	0.004	0.006	0.004	0.005
0.006	0.004	0.003	0.003	0.004	0.004	0.004	0.006
0.014	0.009	0.004	0.004	0.007	0.007	0.005	0.014
0.026	0.014	0.006	0.005	0.007	0.007	0.004	0.026
0.039	0.014	0.004	0.004	0.004	0.004	0.003	0.039
x	0.024	0.007	0.004	0.006	0.004	0.003	x
x	x	0.024	0.014	0.014	0.009	0.004	x
x	x	x	0.039	0.026	0.014	0.006	x
0.024	x	x	x	0.039	0.014	0.004	0.024
0.014	0.039	x	x	x	0.024	0.007	0.014
0.014	0.026	0.039	x	x	x	0.024	0.014
0.009	0.014	0.014	0.024	x	x	x	0.009
0.004	0.006	0.004	0.007	0.024	x	x	0.004

For image reconstruction, these data were simulated using EIDORS and the result is shown in figure4.4.

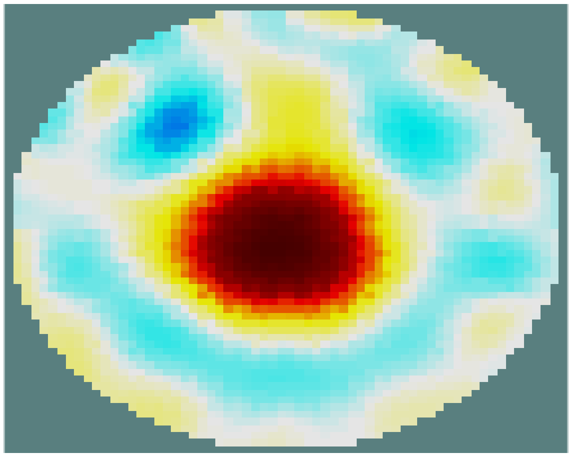


Figure 4. 4: Resistivity Image Created by EIDORS with tumor in the middle of the phantom

4.2 Discussions:

4.2.1 EIT system cost:

The overall cost of our Arduino based EIT system is lower than microprocessor, microcontroller or DSPs based EIT systems. It costs only 63.61$ (as shown in table 4.1) while microcontroller or microprocessor based systems costs 322$ and DSPs based systems costs 313$.

Table 4. 4: The overall cost of the EIT system.

Nu.	Component	quantity	Price ($)
1	Signal source	1	7.98
2	Voltage controlled current source (VCCS)	1	10
3	Ag/Agcl Electrodes	16	12.28 /lot (100 electrodes/lot)
4	16 channel CD4067B Multiplexors	4	6.35
5	Arduino mega1280	1	5.88
6	741 Opamp	2	1.55 (for 10 pieces)
7	Resistors	8	(0.22-0.52)/lot (100 pieces/lot)
	Total		**63.61**

4.2.2 EIT system performance:

4.2.2.1 Use of calibration phantom:

As previously mentioned, when using calibration phantom, the 208 voltage measurements must be identical and it depends only on the value of one resistor (1Ω). By injecting (5 m A) AC current, the resulted RMS voltage values should be:

$$(1\Omega) \text{x} \ (5 \text{ m A}) \text{ x } (0.707) = 0.003535 \text{ V}$$

The value obtained using Proteus simulation is (0.004V) which is approximately equal to (0.003535 V).So the system has an accuracy of:

$$\left(\frac{0.004\,V - 0.003535V}{0.003535V}\right)\% = 13.15\%$$

4.2.2.2 Use of Cardiff phantom:

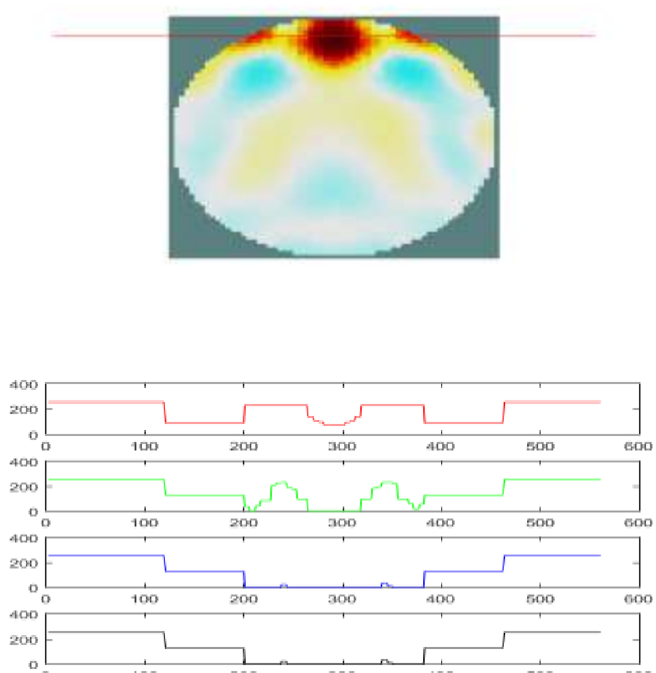
4.1.2.1.1 Tumor position:

Our EIT system gives the exact position of the tumor as shown in figure 4.2, figure 4.3 and figure 4.4 for tumor close to electrode-1, between the center of the phantom and electrode-6 and at the middle of the phantom respectively.

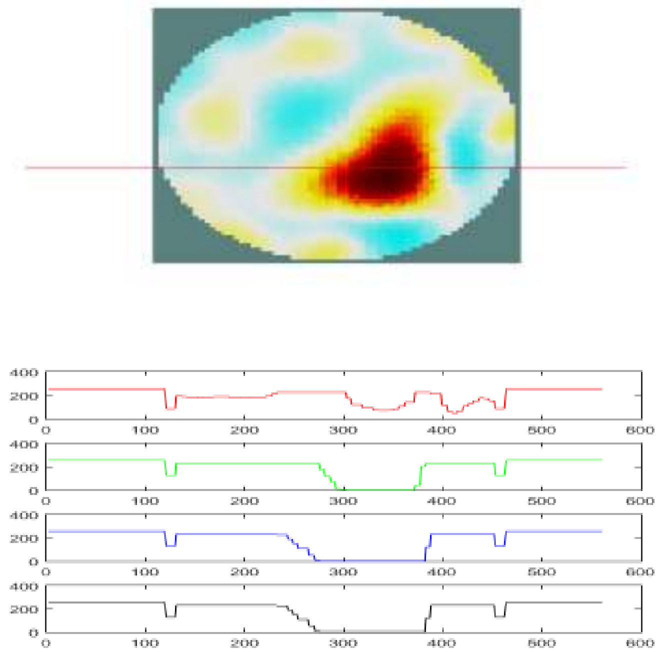
4.1.2.1.2 Tumor size:

According to Cardiff phantom design, only four pixels values in the image should change when applying equation (1) and (2). To confirm this, intensity profile for the three images with tumor at three different positions was obtained as shown in figure 4.5.

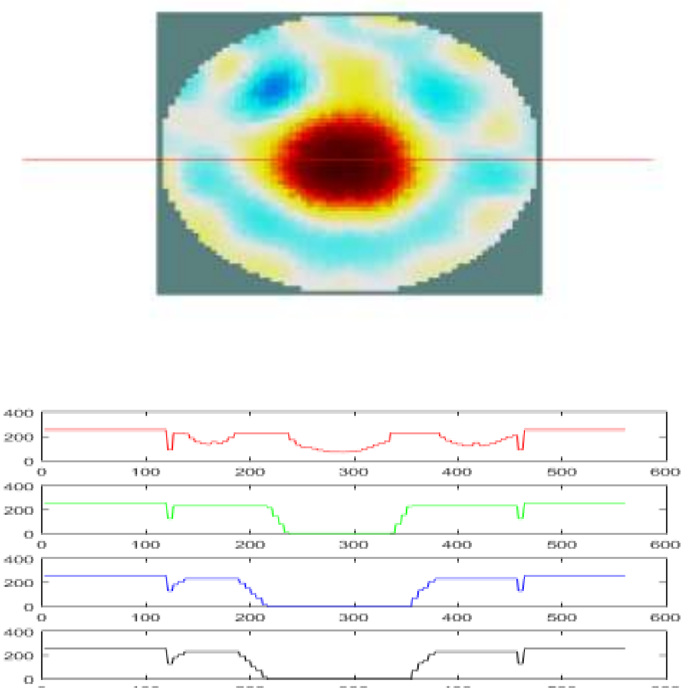
The intensity profile for the three reconstructed images shows that more than four pixels were changed and this interprets the large size of the tumor in the reconstructed images compared to the actual tumor size in the phantom especially when the tumor is close to the center of the phantom.



(a)



(b)

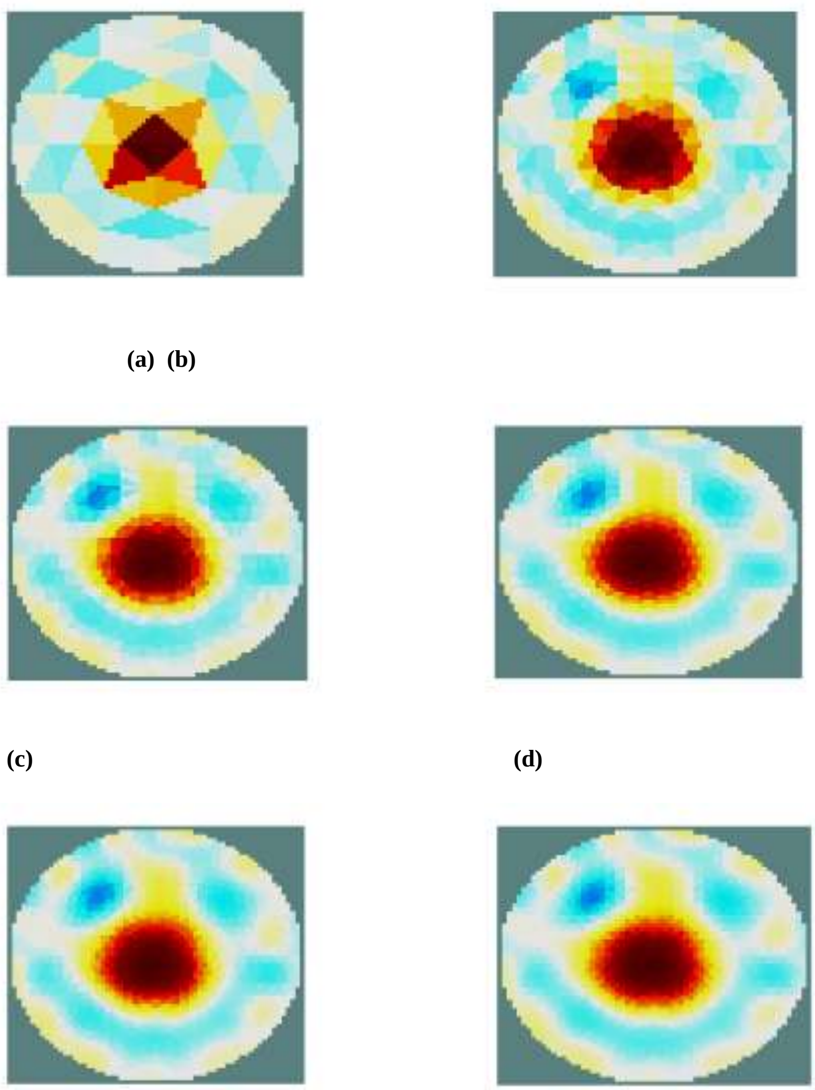


(c)

Figure 4. 5: intensity profile (RGB and gray image) for (a) reconstructed image with tumor at electrode-1 (b) reconstructed image with tumor between the center of the phantom and electrode-6 (c) reconstructed image with tumor at the middle of the phantom.

4.1.2.1.3 Spatial Resolution:

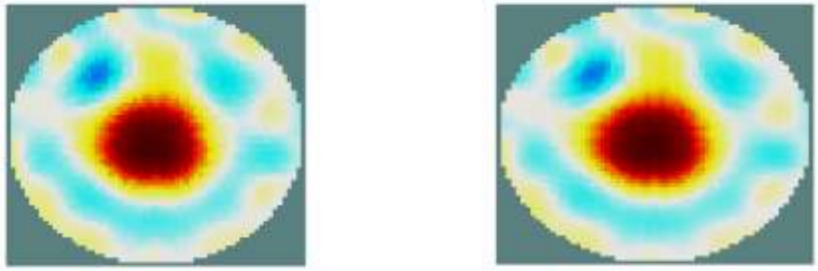
In EIDORS, Reconstruction of EIT image using inverse problem solution (Appendix B) requires 2D phantom model building. Here we built 2D -16 electrode circular phantom in which spatial resolution depends on the number of phantom elements used.as the number of elements increase, better spatial resolution image is reconstructed as shown in figure 4.6.



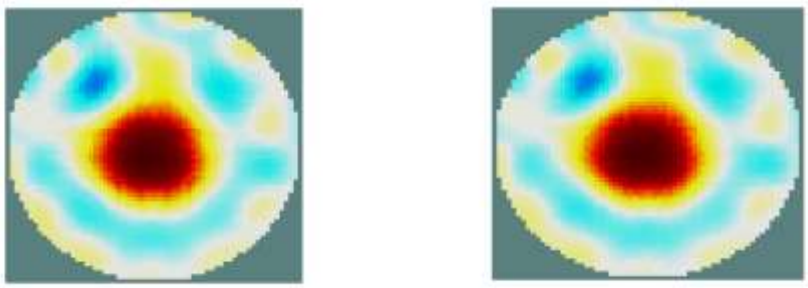
(a) (b)

(c) **(d)**

(e) **(f)**



(g) (h)



(i)**(j)**

Figure 4. 6: reconstructed image with tumor at the center of the phantom using (a) 64 elements. (b) 256 elements. (c) 576elements. (d) 1024elements. (e)1600elements. (f) 2304elements.(g)3136 elements. (h)4096 elements (i) 5184 elements.(j)6400 elements.

4.1.2.1.4 Data acquisition time:

The simulation time taken from injecting the current until receiving the data on the Excel sheet is about 15 minutes, but real time required to take one measurement is about:

$$(500 * 1msec) = 0.5\ sec$$

As 1ms is enough to make publish ( ), update ( ) and analogread ( ) function the required time for 208 measurements:

$$0.5 * (208) = 104\ sec$$

$$= \frac{104}{60} = 1.7333\ min$$

This variation between simulation and calculated real time is due to the complexity of the Cardiff phantom. As we observed that by experimenting the same circuit with less complex phantom, the simulation time decreases.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

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CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion:

Our goal was to design a simple and low cost EIT system; we successfully achieve this goal by using Arduino microcontroller as an analog signal processor which is a compact package that eliminate the need for discrete components leading to simplifying the design and lowering its cost to be of about 63.61$.

In addition our system gives the correct result (with small ignored error) and gives the exact position of the tumor with high spatial resolution in a real time of about 1.7333 minutes (simulation time of about 15 minute). But it fails to give the exact size of the tumor as it obvious in the results.

Our EIT system could be used for screening human body (such as: lung, breast.. etc.), so it can be an alternative tool for imaging systems that use ionizing radiation making it possible for developing countries like Sudan to own imaging systems especially in rural and urban areas where imaging tools are not found or few due to its high cost.

5.2 Recommendations:

It was observed that our EIT system does not gives the exact size of the tumor , Further forward and inverse problem solvers existing in EIDORS can be tested to determine which one provides the most satisfactory results.

Also data acquisition can be faster and accurate by replacing the Arduino microcontroller with another Arduino microcontroller that owns more than 16 MHz crystal.

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REFERENCES

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APPENDICES

Appendix A

Arduino codefor the first, second and third current injection

```
//library of the multiplexors
#include <CD74HC4067.h>
//library for calculating RMSvalues
#include <TrueRMS.h>
// loop period time in microseconds (time between samples)
#define LPERIOD 1000
// define the used ADC input channel
#define ADC_INPUT 0
// RMS window of 40 samples, means 2 periods at 50Hz
#define RMS_WINDOW 40
unsigned long nextLoop;
int adcVal;
int cnt=0;
// ADC full scale peak-to-peak is 5.00Volts
float VoltRange = 5.00;
// create an instance
Rms readRms ;
CD74HC4067 my_mux(22,23,24,25);
CD74HC4067 my_mux2(26,27,28,29);
CD74HC4067 my_mux3(30,31,32,33);
CD74HC4067 my_mux4(34,35,36,37);
void setup()
{
Serial.begin(9600);
Serial.println("LABEL,v");
Serial.print("DATA, ");
readRms.begin(VoltRange, RMS_WINDOW, ADC_10BIT, BLR_ON,CNT_SCAN);
readRms.start();
// Set the loop timer variable for the next loop interval.
//micros( ) Returns the number of microseconds since the Arduino
board began running the current program.
nextLoop = micros() + LPERIOD;
```

```
//electrode 0 and 1//electrode 0 and 1
my_mux.channel(0);
my_mux2.channel(1);
for (int k=2;k<15;k++)
{
my_mux3.channel(k);
my_mux4.channel(k+1);
for(int i=0;i<500;i++)
{
// Read the ADC and remove the DC-offset
adcVal = analogRead(ADC_INPUT);
//take an instance again
readRms.update(adcVal);
cnt++;
//repeating the readings of one sample
if(cnt >= 500)
{
// publish every 0.5s
readRms.publish();
Serial.print(readRms.rmsVal,3);
Serial.println();
Serial.print("DATA, ");
cnt=0;
}
// wait until the end of the time interval
while(nextLoop > micros());
// set next loop time to current time + LOOP_PERIOD
nextLoop += LPERIOD;
}
}
//electrode 1 and 2//electrode 1 and 2
my_mux.channel(1);
my_mux2.channel(2);
for (int k=3;k<15;k++)
{
```

```
my_mux3.channel(k);
my_mux4.channel(k+1);
for(int i=0;i<500;i++)
{
// Read the ADC and remove the DC-offset
adcVal = analogRead(ADC_INPUT);
readRms.update(adcVal);
//take an instance again
cnt++;
//repeating the readings of one sample
if(cnt >= 500)
{
// publish every 0.5s
readRms.publish();
Serial.print(readRms.rmsVal,3);
Serial.println();
Serial.print("DATA, ");
cnt=0;
}
// wait until the end of the time interval
while(nextLoop > micros());
// set next loop time to current time + LOOP_PERIOD
nextLoop += LPERIOD;
}
}
my_mux3.channel(15);
my_mux4.channel(0);
for(int i=0;i<500;i++)
{
// Read the ADC and remove the DC-offset.
adcVal = analogRead(ADC_INPUT);
readRms.update(adcVal);
//take an instance again
cnt++;
if(cnt >= 500)
```

```
//repeating the readings of one sample
{
// publish every 0.5s
readRms.publish();
Serial.print(readRms.rmsVal,3);
Serial.println();
Serial.print("DATA, ");
cnt=0;
}
// wait until the end of the time interval
while(nextLoop > micros());
// set next loop time to current time + LOOP_PERIOD
nextLoop += LPERIOD;
}
//electrode 2&3//electrode 2&3//electrode 2&3
my_mux.channel(2);
my_mux2.channel(3);
my_mux3.channel(0);
my_mux4.channel(1);
for(int i=0;i<500;i++)
{
adcVal = analogRead(ADC_INPUT);
readRms.update(adcVal);
cnt++;
if(cnt >= 500)
{
readRms.publish();
Serial.print(readRms.rmsVal,3);
Serial.println();
Serial.print("DATA, ");
cnt=0;
}
while(nextLoop > micros());
nextLoop += LPERIOD;
}
```

```
for (int k=4;k<15;k++){
my_mux3.channel(k);
my_mux4.channel(k+1);
for(int i=0;i<500;i++)
{
adcVal = analogRead(ADC_INPUT);
readRms.update(adcVal);
cnt++;
if(cnt >= 500)
{
readRms.publish();
Serial.print(readRms.rmsVal,3);
Serial.println();
Serial.print("DATA, ");
cnt=0;
}
while(nextLoop > micros());
nextLoop += LPERIOD;
}
}
my_mux3.channel(15);
my_mux4.channel(0);
for(int i=0;i<500;i++)
{
adcVal = analogRead(ADC_INPUT);
readRms.update(adcVal);
cnt++;
if(cnt >= 500)
{
readRms.publish();
Serial.print(readRms.rmsVal,3);
Serial.println();
Serial.print("DATA, ");
cnt=0;
}
```

```
while(nextLoop > micros());
nextLoop += LPERIOD;
}
```

Appendix B

MATLAB code for image reconstruction

```
% load data
x=xlsread('normal.xlsm');
y=xlsread('at1.xlsm');
calc_colours('greylev',-.01);
% select the 2d model reconstruction
imdl= mk_common_model('g2c');
% select the stimulation pattern
imdl.fwd_model.stimulation=
mk_stim_patterns(16,1,[1,0],[0,1],{'no_meas_current'},5);
vi=real(x);
vh=real(y);
% select the reconstruction mode static or diferential
inv_model.reconst_type = 'difference';
% reconstruction solution
img= inv_solve(imdl, vh, vi);
img.calc_colours.greylev = -.1;
%view the reconstruction
show_slices(img);
```