ECEN 4610 – Capstone Laboratory

Electrical Impedance Tomography Machine Design: An Open-Source Approach

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Contents

1 Executive Summary

Electrical Impedance Tomography (EIT) is a non-intrusive medical imaging technique for viewing a cross section of an area [1]. Common imaging applications include the viewing of the heart and lungs, brain, and breast tissue. Two currents 180 degrees out of phase into a plane of the human body. Electrodes surrounding the cross-sectional area of the body are used to measure varying voltages to create an image showing the varying impedance, conductivity, and permittivity throughout the tissue plane. This document outlines the design of an EIT machine using programs and hardware aimed at creating cheaper and more open-source methods of manufacturing, that are accessible to the general public and university students.

2 Problem Definition

2.1 PROBLEM SCOPE

This paper documents the design and construction of an EIT machine using methods and hardware that are accessible to the general public and university students. The project sponsor for whom the development of the EIT machine is being done is Dr. Talles Santos, a professor of electrical engineering who is working for the University of Colorado, Boulder.

The project sponsor has extensive experience in high quality EIT machine development and research. Motivated by a desire to continue the research in EIT and make the technology more accessible, the project sponsor would like to use continued development of EIT to educate students in the application of the technology. The project sponsor has experience working with other grad students and professors on the development and construction of EIT machines and would like to expand its development to include the work of under grad students. Currently there is no EIT machine at the location of Colorado Mesa University (CMU), where the project sponsor is physically located and works. This project will be the beginning of a goal to make CMU a new center for the development of the technology.
The project sponsor has tasked the 2022-20123 senior design team with starting a path to creating a fully open-source model for the construction of an EIT machine. Using components available and relatively inexpensive integrated circuit (IC) components, a fully functional EIT machine with real-time imaging is to be constructed. The construction of the EIT machine was to maintain a cost below $3,000.00 of the total budget.

2.2 TECHNICAL REVIEW

2.2.1 INDUSTRY BACKGROUND

Electrical Impedance Tomography (EIT) is a noninvasive medical imaging technique. The imaging technique uses alternating current (AC) that is injected into the human body to create a tomographic image of a cross sectional area. Voltages are read through electrodes placed on the surface of the skin surrounding the area to be imaged. The voltage readings are then used along with the injection current to calculate variations in impedance, conductivity, and permittivity through the biological tissue to create the tomographic image of the cross-sectional area.

Direct Current (DC) and low frequency electricity does not pass easily through biological tissue. Which is the reason why higher frequency AC electricity is needed. There is significant variation in impedance, conductivity, and permittivity between different types of biological tissue. This variation in impedance is what allows for the production of tomographic images of the body. Variation in impedance is due to the free ion content of tissue. Electrical impedance is shown by the expression in Equation (1) [2].

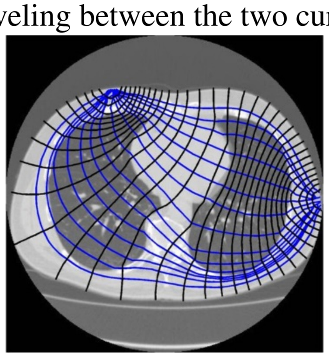
$$Z = R + jX \tag{1}$$

Where Z, the electrical impedance, is equivalent to R, the resistance, and X the reactance. Conductivity and permittivity are typically what is used in the actual imaging of tissue. Conductivity is the reciprocal of impedance and is expressed in Siemens per meter (S/m). Typically, the more fluid filled tissue is, the more conductive it is. Typical values for conductivity are shown below in Table 1. A specific organ of note, the lungs, has much higher impedances than other organs. This is because air has a very high impedance.

Table 1: Shows the difference in conductivity between different tissue types[1]

Tissue	**Conductivity** ($^{mS}/_{m}$)
Cerebrospinal Fluid	1450-1800
Blood	500-650
Scalp	300-420
Brain	300-400
Muscle	200-400
Fat	50
Bone	6

The differences in conductivity are mapped out using electrical excitation caused by two injection current sources. These two injection currents have the same frequency and amplitude but are 180° out of phase from each other. While one injection current is positively charged, the other will be negatively charged. In conventional current terms, current will flow from positive charge to negative charge. Electrodes surrounding the tissue are used during the current injection process to take voltage readings. Current injection sites are at the same locations as the electrodes, but only 2 at a time are activated at once. The turned-on current injectors rotate to the next injectors after a period of time that is optimal for the measurement process. The current injectors that are turned on depend on the process chosen. Figure (2) shows a visualization of the injected currents streamlines traveling between the two current injection sources.



2.2.2 CLIENT BACKGROUND

Dr. Talles Santos received his Bachelor of Science degree in electrical engineering from the federal University of Minas Gerais, Belo Horizonte, Brazil, in 2012, Earned a master's degree in 2015 and his PhD in 2019, both in control engineering and mechanical automation from the Polytechnic School at the University of São Paulo, Brazil.

Dr. Santos has more than 10 years of experience in the EIT field. He worked part time at Timpel Medical, São Paulo, Brazil, working on EIT development [3]. Also, he has worked with several other groups developing EIT for medical applications. Currently he is a professor of electrical engineering who is working for the University of Colorado, Boulder. He now wants to start further development of EIT technology at CMU, while using the opportunity to educate students in the principles of how EIT works and how to construct a machine. Dr. Santos wants to make the technology cheaper and more accessible to medical professionals and individuals who want to study and help further develop the technology [3]. EIT machines require the coordination of high frequency current injection, sampling processes, and control circuitry at high speeds in order to achieve real time imaging with a resolution that is usable for a medical professional. The construction of such a machine is a lot of work for one individual to undergo. The sponsor requires the assistance of other individuals well versed in electrical and computer engineering, which is the reason why the 2022-2023 capstone team has been tasked with assisting the sponsor in the construction of an EIT machine.

2.2.3 CURRENT PROCESS

Currently there is no EIT machine working or in development at CMU. This project will be the beginning of its development at CMU.

2.2.4 EXISTING SOLUTIONS

The existing solutions for this project are made by companies with closed solutions. Some of the existing manufacturers are Timpel (Dr Santos' former employer) [3], Sentec [4], Drager [5], and Sciospec [6]. Sciospec replied to the team with a quote for a medical grade 64 channel EIT machine the price is about $60k. This is outside the budget of the sponsor, and it severely limits the modifications that can be made to the device. In addition, the sponsor wants the project to be more open source and to not use proprietary or expensive commercial hardware.

This means that this project will be building each component from the ground up. The project sponsor has many years of experience in EIT application and research. There are three major components to design. First is a current injection system, second is the measurement system, third is the control system.

First, the current injection system, which injects current into the patient to be measured by the measurement system. There are specific methods of current injection patterns, creating a stable current injection source, and signal extraction that were recommended. For current injection, the skip four method was recommended by our sponsor. The skip four method is when the bipolar current injection is done between two electrodes spaced 4 electrodes apart, at all times. There are no current sources that would match our requirements and that would be within our price range.

Second, the measurement system has three main requirements. First is the precision of the system, second is the sampling frequency, and third is synchronization of the measurements. The sponsor provided two National Instruments PCI-6259 DAQ boards (NI boards for short) for the project. These boards are 125 kS/s when using 32 channels that will have 1mV precision with the ability to synchronize all the channels together.

Third, the control system, which oversees the current and measurement systems so they can work together. This system needs to have the processing power to run faster than the current and measurement systems to be able to coordinate the systems together. There are many existing solutions for the control system. Diego has proved an old desktop to use. The desktop has the ability to connect the two measurement boards to the motherboard and use the software to collect data and process it into an image.

2.3 DESIGN REQUIREMENTS/CRITERIA and Engineering Standards

The project deliverable is a functioning EIT machine capable of:

- Three-Frequency Signal Generation
  - Ideally consisting of 80, 100, and 120 kHz frequencies
  - 10mA RMS current injection
    - Accurate within 0.1mA
- 32 Channels of voltage readings
  - Sample size (500 - 1024)
  - Use the two provided NI PCI-6259 DAQ boards (NI boards)
    - Highest sampling rate possible with NI board
    - Maximum rate of 1 MS/s single channel possible
- Real-Time imaging
  - Ideally 32x32 bits
- Buffer between measurement and electrodes
- Control system to map the current delivery to desired electrodes
  - Synchronizes with measurement process
  - Implements the ”skip 4 method”
- Safely limit current
  - To ensure test subjects are not shocked
  - To provide redundancy in power supply current protection
- Implement central control through the use of a desktop computer
  - Use the computer monitor to display the real time imaging

- Develop a working process to rapidly prototype PCB boards
- Use MATLAB to display imaging and process data

Three frequency current injection into the test subject is necessary for various reasons due to the impedance characteristics of biological tissue as described in section 4.2.1. Three frequency current injection is favored as an optimal way that the sponsor has found to get a more precise image. The 10 mA rms current amplitude is considered by the sponsor to be sufficient to provide voltage readings that will be above noise levels at a level that makes taking the voltage readings possible, without injecting too much current that it becomes unsafe for a patient. The skip four method of current injection has been shown through the sponsor's research to be the most effective way to inject current for good imaging. The skip four method is when the two current injection sources are spaced 4 electrodes away from each other, and this pattern alternates in a clockwise pattern.

Thirty-two channels of voltage readings from the electrodes are necessary to construct an image of the quality the sponsor is hoping to achieve. Too low of a resolution on the image will leave the image obtained from the device too difficult to be useful for medical purposes. These 32 voltage readings are necessary to achieve a 32x32 bit image. A minimum of 500 samples should be acquired in a buffer during the sampling measurement process, with an ideal target 1024 samples.

Use of the NI boards provided is desired by the sponsor because it has already existing toolboxes and has drivers available for simple integration with MATLAB, which the sponsor desires for data processing and imaging.

The desktop will be used for controlling the devices and for allowing modular design as swapping in and out parts will be easier. The desktop will be able to control the current injection source and the measurement system at the same time to produce synchronized data. Then the desktop will have the power to process the data into an image as the measurement system takes another set of data to be processed. Implementing a computer for central control in this way will simplify operation of the EIT machine for the sponsor.

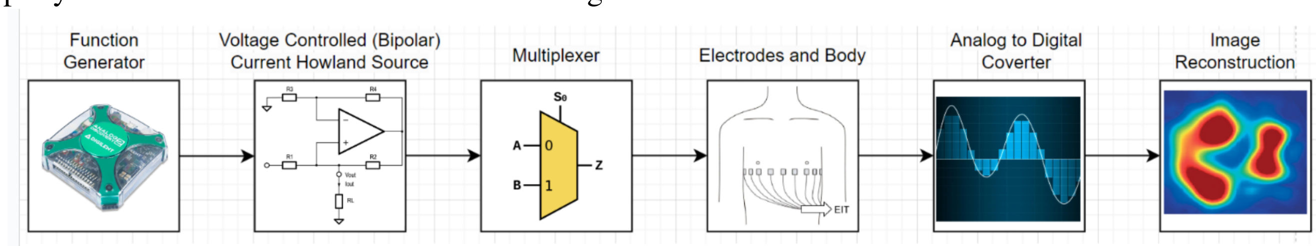
Published by the International Electrotechnical Commission (IEC), IEC 6061 is a list of technical standards for the safety and performance of medical electrical equipment [7]. These standards are considered as necessary in many countries by law and is widely accepted as a necessary list of requirements for product development for many companies and corporations. Another set of standards provided by the American National Standard Institute is the ANSI/AAMI ES60601-1:2005, which also includes standards on electrical equipment [8]. Standards that may apply to the development of the EIT machine include calibration of the ADC and electrical safety standards.

3 Design Description

3.1 OVERVIEW

A computer with adequate clock speeds is critical to control multiple running processes at the necessary speeds. A central computer will be necessary to control and coordinate all the machine's components and processes. From this central control desktop computer, two NI boards generate and read analog voltage signals and digital signals. The generated analog voltage signals are used to control a current source for injection into the test subject. The electrodes receive the injection current directed by the control circuit, controlled by the NI boards' digital output pins. While the current injection is constantly occurring, the NI board reads all 16 electrodes placed around the test subject. These analog signals read from the electrodes are then collected by a program and used to generate a real-time image.

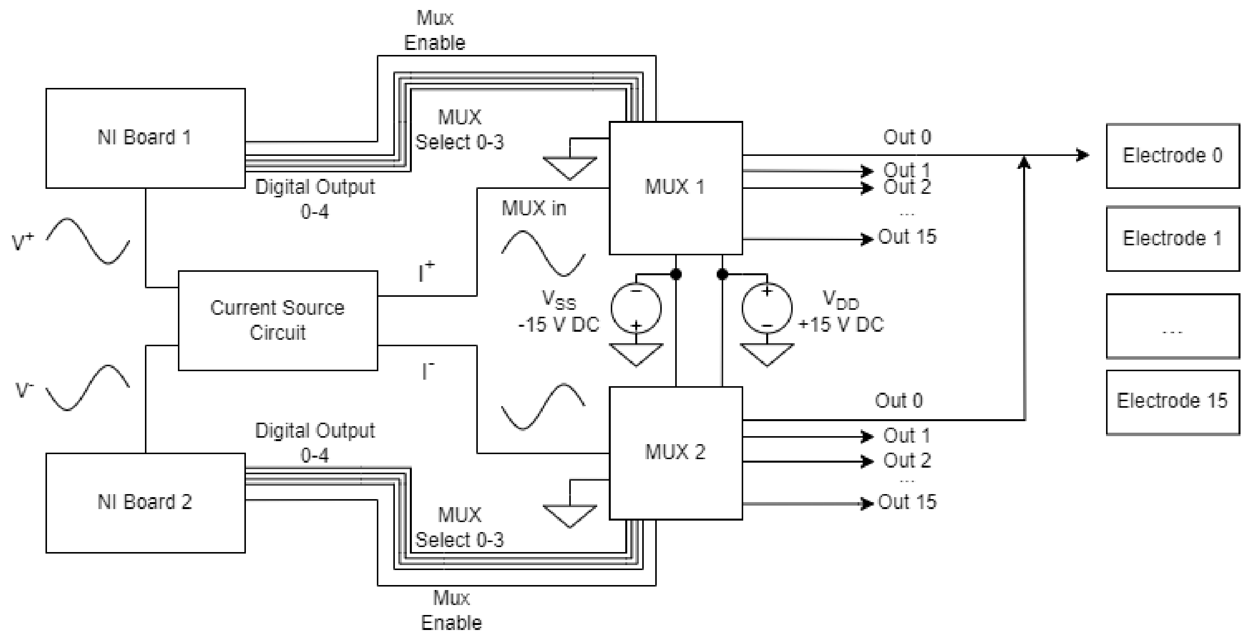
Coordinated by the control desktop using the NI Boards, a small multifrequency signal is sent through a voltage controlled current source. The signal is restricted to a consistent output despite the body's various impedances. Then the signal is directed to the body's active electrodes using the digital logic from the desktop to the multiplexers. Using the same active electrodes, the signal is both sent and read. The signal data is sent to the MATLAB (software) script where the signal is properly extracted and reconstructed into the image.



3.2 DETAILED DESCRIPTION

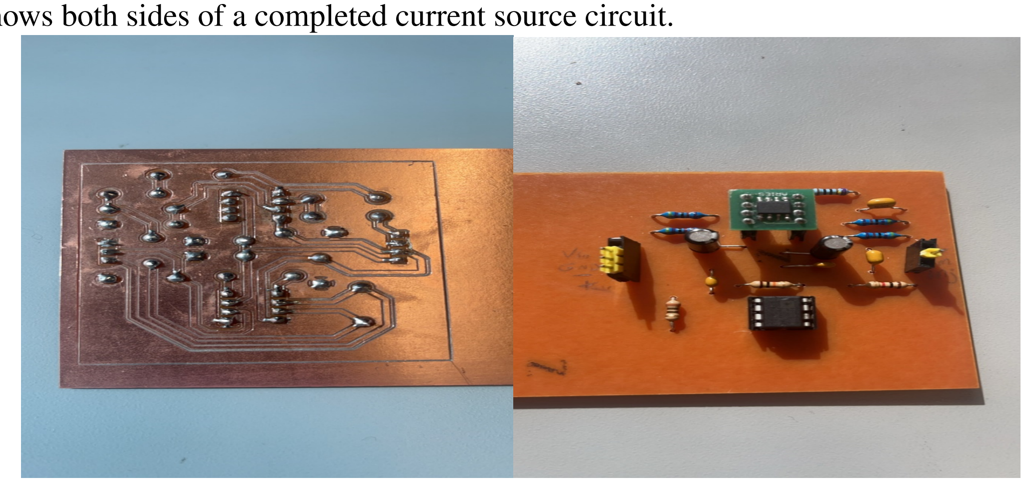
3.2.1 SYSTEM/COMPONENT 1 - Control

The control system circuit consists of two 16:1 multiplexor (MUX) ICs. The specific component used in the design was the ADG406BNZ, from Analog Devices Inc. These MUXs are designed to direct 16 different signals to or from one destination or source. The MUXs are being used to direct a current from a respective Howland current source to one of 16 electrodes. The 16 MUX outputs connect the 16 electrodes with the NI Boards read channels and are directed by 4 digital control signals. Connecting each output of the MUXs will halve the amount of wire needed and will not be an issue because the MUXs will not have the same channels, permitting current flow at the same time. A single 12 V supply will power the MUXs. A simple diagram of the control circuit is shown in Figure 3.



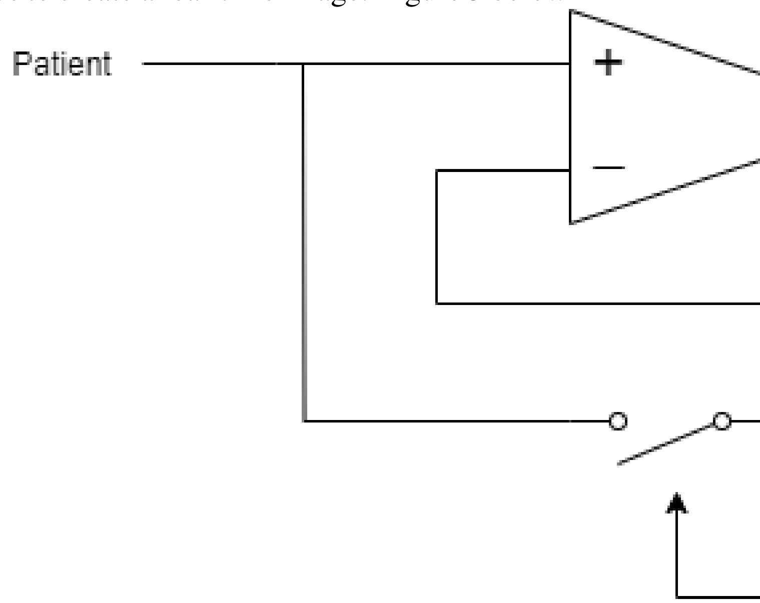
3.2.2 SYSTEM/COMPONENT 2 – Current Injection

The current injection system consists of a multifrequency bipolar signal. The signal contains a 10k, 25k, and 50k Hz signal with a peak current of 10mA. The signals will be generated using the NI boards 180 degrees out of phase. The signal will then be sent through the Howland current source where the current is restricted. The body has a varying impedance as the patient breathes and the Howland current source keeps a constant current output while impedance varies. Figure 4 below shows both sides of a completed current source circuit.



3.2.3 SYSTEM/COMPONENT 3 - Measurement

The measurement system consists of 16 electrodes and two NI boards. The NI boards read analog voltage signals from electrodes, which pick up voltages created by the current injection system. The electrodes have buffers that isolate the patient from the NI board and the current directed by the MUX control circuit. The voltages read by the NI board are then processed by a program written in MATLAB to create with code supplied by Dr. Santos to create a real-time image. Figure 5 below



shows a simple layout of the active electrode circuit.

3.2.4 SYSTEM/COMPONENT 4 – Power Supply

The power supply system provides power to all the IC components; each requiring a different voltage. The first component running from a 60Hz, 120 V, standard AC wall outlet is a 120 V AC to 24 V DC converter. Following this converter is multiple DC to DC converters. A 24 V DC to plus and minus 15 V DC converter is used to provide power to the two MUXs of the control circuit and provide power for the current source circuit.

3.3 USE

To be completed Later

4 Evaluation

4.1 Overview

The test plan for the EIT machine requires testing on many components. To be confirmed was that two three-frequency voltage signals, consisting of 10, 30, and 50 kHz, 180 degrees out of phase, were produced by the NI board that was to be then converted into a current signal that was not to exceed 10 mA, with a 1% margin of error for accuracy. This current signal delivery system was tested for accuracy and consistency with voltage measurements by taking voltage measurements with an oscilloscope over a resister.

A control system was also tested to ensure that timing and current direction would be delivered to the appropriate electrodes at the appropriate time. Testing of the control system was done by measuring voltage signals at the electrodes while stepping through the control system slowly while ensuring that the proper electrode was receiving the signal. The control system was also to implement the skip-four pattern of current injection.

The voltages produced on the electrodes were then to be read back in by the ADC of the NI boards to processed by a MATLAB script. Ideally this was to be done over 32 electrodes, at a sample rate of 1 Ms/s, verified by settings designated by the created MATLAB script. At each each phase of measurement, a single state of electrode current injection was to provide a sample size between 500 to 1024 samples, which was simply verified by viewing variables in MATLAB. MATLAB was also to be used to provide real-time imaging, which would be verified by viewing a real-time image of an object easily confirmed by placing objects in a saltwater tank. A signal extraction technique was used to extract only the desired input frequencies called Quadrature Demodulation and was tested greatly to ensure its accuracy.

Current into the system used to power all circuitry needed to be current limited as well to ensure safety. This was done by simply using adjustable DC voltage sources using a single Gw Instek GPP-3323 DC power supply. All circuits were to be done on CNC milled PCBs, was shown to be completed with physically created PCBs that were implemented into use on the EIT machine.

Table 4.1.1. Contains base requirements for EIT system.

	Target	Method
1	Bipolar multifrequency injection current is up to 50 kHz at 5-10 mA	User testing
2	Curren varies less than 1% from 200 – 2000 ohms	User testing
3	Sample Rate at least 125 KS/s	User testing
4	Open Source	User evaluation

4.2 Evaluation of Howland Current Source Circuit and Signal Generation

4.2.1 Purpose of Evaluation

The signal sent to the patient must maintain a stable current across the load resistance ranging from 500 to 2000 ohms. This requirement arises from the fluctuating resistance within the patient's body, particularly during breathing cycles and lung inflation. It is crucial to limit the deviation in current across these impedance ranges to within 1% to accurately capture the patient's impedance data, preventing distortion caused by signal artifacts. The Howland current source employs DC-blocking capacitors at the signal output to guarantee patient safety by preventing electric shocks.

4.2.2 4.2.2 Test Methods

A single Howland circuit was tested with a variation of loads with an input signal at the maximum frequency of 50kHz and a 6Vpp signal. This expected approximately 7.75 mA output at 50kHz. This test allows the current to be as high as possible without beginning to saturate.

4.2.3 4.2.3 Results and Discussion

When the current surpasses 8mA at 1500 ohms, the output signal begins to saturate due to the operational constraints of the Howlands AD8066 IC, which is powered by +/- 12 volts and cannot exceed this output value. To accommodate a resistance load of up to 2000 ohms, the design is limited to utilizing up to 6 mA. Considering the system will be tested on a tank with a resistance load of no more than 1500 Ohms, a current of 7.75 mA is applied to optimize performance while avoiding saturation, as indicated in Table 2. The table also displays an injection current error within 6.4%. Despite this proximity to the expected accuracy, it falls short of the desired 1% threshold set by our sponsor. Consequently, the generated images may exhibit minor distortion if impedance fluctuates between the minimum and maximum values.