Development and evaluation of a low cost 8-electrode Electrical Impedance Tomography system

C E Castillo and A E Álvarez
Electronics and Computing Division, Electronics Department, University Center for Exact Sciences and Engineering, University of Guadalajara, Blvd. Gral. Marcelino García Barragán 1421, Guadalajara, México.

E-mail: carlos.castillo6190@alumnos.udg.mx, angel.alvarez7582@alumnos.udg.mx

Abstract. Electrical impedance tomography (EIT) is a medical imaging modality that considers the electrical properties of tissues to obtain a conductivity distribution of a region of interest using the level of resistance it presents to the passage of a small electrical current. This work describes the design of an 8-electrode EIT prototype that offers the possibility of changing the excitation parameters and freedom of movement of the demodulation synchrony by means of conventional electronics. The image reconstruction obtained can locate disturbances in the study medium using the adjacent electrode method. A comparison of the voltage measurements acquired on a homogeneous test medium in two different collection cycles was implemented to determine the precision of the system. The data obtained indicate a maximum error percentage of 2.6% between measurements, which represents an acceptable first approach towards the design of a device with greater stability and precision.

1. Introduction
Electrical impedance tomography (EIT) is a medical imaging technique that uses the physical principle of the impedance to generate a conductivity map of the study area from surface voltage measurements [1]. In the medical field, it is currently used to detect and evaluate the treatment of lung diseases [2], the characterization of cancerous tissue in the body [3], or the estimation of the level of osteoporosis in the bones [4], to name a few. The technique can produce three-dimensional and two-dimensional images of the cross-section of the impedance distribution, or conductivity, in a conducting body, which is different for each tissue [1].

The EIT reconstructed image is based on measurements of surface voltages resulting from a rotatory injection of low intensity alternating current between electrodes located on a circumference that surrounds the studied object. The current is weak enough that it doesn’t cause a feeling of discomfort or burn body tissues as an electric shock [5]. The technique has the advantages of being portable, simple, fast, easy to use, low cost, comfortable for the patient, non-invasive and safe as it is completely based on electronic instrumentation [6].

The resulting image of an EIT reconstruction of is highly dependent on the instrumentation (hardware) and its ability to produce accurate information, as well as the ability of the reconstruction algorithm (software) to interpret the data and reconstruct it into an image [7]. The number of electrodes in the system can be variable, increasing the resolution of the images as more are used, normally the array is made up of 8, 16 or 32 [1]. However, in applications that require high acquisition
speed, or the need for portability and miniaturization, the minimum number of electrodes possible is used, sacrificing image quality [8]. The instrumentation blocks that make up an EIT system consist of the implementation of a waveform generator [7], a constant current source [5], a multiplexer system, a synchronous demodulator or voltmeter, a differential amplifier, and a control system [9].

In this paper, an alternative is presented for the construction of a low-cost EIT system considering each of its elements. The evaluation of the precision of the prototype was carried out by collecting voltage samples from an 8-electrode phantom with a homogeneous medium and a subsequent comparison of the data obtained after the collection of two complete cycles of current injection and voltage reading.

2. Materials and Methodology
The proposed system design consists of 6 stages: A Voltage-Controlled Oscillator, a Voltage Controlled Current Source, a synchronous sampling demodulator, a multiplexing system, an acquisition stage, and a data reading and control block.

2.1. Voltage-Controlled Oscillator (VCO)
The sinusoidal voltage signal was produced using an ICL8038 waveform generator, an integrated circuit capable of producing a high-precision sine wave, the wave characteristics are provided by the elements external to the integrated. The frequency selection range is from 0.001 Hz to 300 kHz. For this work, the frequency used was 1 kHz and an amplitude of 1Vpp. Passive high pass and low pass filters were implemented at a cut-off frequency of 159 Hz and 4.8 kHz respectively, later a voltage follower was added before the completion of the stage. The amplitude of the output wave can be regulated by a voltage divider controlled by the variable resistance \( R_{V1} \) shown in figure 1.

\[
R_1 = R_2 = R
\]

The wave frequency \( f_s \) is determined by (1):

\[
f_s = \frac{0.33}{RC_1}
\]

2.2. Voltage Controlled Current Source (VCCS)
A precision voltage-to-current converter was implemented using an AD620 instrumentation amplifier. A LF412CN operational amplifier is used as a buffer for the AD620 reference terminal to maintain good common mode rejection (CMRR). The output voltage of the AD620 is reflected in the resistor \( R_{18} \) shown in figure 2, producing the amount of current that will pass through the load, so the calculation of the output current depends exclusively on the value of that resistor, as shown in (2).

\[
I_L = \frac{V_+}{R_{18}}
\]
2.3. Synchronous sampling demodulator

Synchronous sampling is based on the principle that the frequency, amplitude, and phase of the generated signal are known variables, so it is possible to synchronize the voltage readings of the obtained signal with the maximum peak of the generated current wave or when it is found in a zero crossing, the goal of synchronous sampling is to obtain a voltage sample at a specific point in time. If the process is sufficiently precise, it is possible to obtain the real or imaginary components of the impedance of the domain [10].

For the implementation of the circuit, the proposed in [11] was used with some changes in the design. The diagram and its result are shown in figure 3.

The input sine wave is conditioned by a buffer amplifier; subsequently its position is adjusted by means of a phase shift circuit through the manipulation of the variable resistor \( RV_2 \). The phase-shifted
signal enters the precision voltage comparator LM393 to be converted into positive voltage pulses which are used as a reference for the edge detection stage implemented through digital gate logic. It is possible to shift the position of the pulses by varying the variable resistor \( R_V \) shown in figure 3(a). The result is a precise signal that establishes the timing of synchronization for the sample and hold circuit in the acquisition stage.

2.4. Multiplexing system

The purpose of using multiplexers is to establish the coordinated current injection paths of the electrodes in turn and the controlled selection of the electrodes whose potential difference will be recorded. In this prototype four CD4052BE analog multiplexers were used: two for the input and return of the constant current, and the other two for collecting the voltage present in every other pair of electrodes. For each multiplexer a digital signal from a controller is required on 3 pins: INH, A and B. While INH activates the multiplexer with a logical 0 and deactivates it with a logical 1, A and B receive instructions from a binary address for two selection channels corresponding to X and Y.

In voltage multiplexers, the output channel X of multiplexer 1 is connected to channel X of multiplexer 2, in the same way the Y channels of both are connected. The two outputs are the inputs for the acquisition stage. On the other hand, in the current multiplexers, for both, the same output channel (X or Y) is connected to the current source, while the other is connected to GND to guarantee the return of current.

2.5. Acquisition stage

The potentials measured in the two outputs of the voltage multiplexers are filtered by a high pass CR circuit with a cutoff frequency of 159 Hz and passed to a LF412 operational amplifier that acts as a buffer, then the signals enters the AD620 instrumentation amplifier in a differential configuration.

After the conditioning in a voltage follower, the analog output enters the LF398N sample and hold integrated circuit, which receives the synchronization pulses from the demodulation stage to only keep that point of measurement to be read by the analog to digital converter (ADC). Finally, a low pass filter with a cutoff frequency of 15 Hz is added to avoid the acquisition of high frequency noise in the acquired DC signal. The circuit diagram is shown in figure 4.

![Figure 4. Voltage measurement acquisition circuit.](image)

2.6. Data reading and control block

A control system is necessary to send the channel selection logic of the analog multiplexers used; also, it must be able to establish communication with a computer to reconstruct the image from the data read from the ADC. To fulfill these requirements an Arduino MEGA 2560 board was implemented, taking advantage of its 10-bit ADC and its ability to establish serial communication with a computer to be used as a MATLAB-Arduino interface.
2.7. Evaluation

After the interconnection of the prototype stages, a test was realized on a phantom with water as a homogeneous medium to determine the precision of the system. Two complete cycles of voltage measurements were taken to perform a similarity comparison between them. The evaluation was carried out by calculating the percentage of error for each of the measurements of each cycle using equation (3).

\[
\% \text{ error} = \left| \frac{\text{Second cycle measurement} - \text{First cycle measurement}}{\text{First cycle measurement}} \right| \times 100
\] (3)

The group of measurements obtained in the first collection cycle were interpreted as base values, while the group of the second collection cycle represented the measured values. The test phantom consisted of a plastic container with a perimeter of 42.3 cm. to which 8 strips of aluminium conductive adhesive tape were conditioned as equally spaced electrodes. Each electrode was assigned an alligator tip to ensure contact.

3. Results

The assembly of the designed stages allowed the obtaining of two-dimensional tomographic images in an 8-electrode phantom that stored water as a reference medium. EIDORS (Electrical Impedance and Diffuse Optical Tomography Reconstruction Software), a freely distributed and modified software package was used for the reconstruction of the impedance images [12].

The adjacent electrode method was implemented for the current injection and voltage collection pattern to obtain a total of 40 potential difference measurements in each iteration completed by the system, and the amount of current used was 1mApp. An example of a 576-element FEM differential image obtained with a prototype built is shown in figure 5, where a disturbance of the analyzed medium located between electrode 6 and 7 was placed.

![Figure 5](image-url)

**Figure 5.** Identification of a disturbance within the phantom. (a) Image of the test medium with an inhomogeneity between electrodes 6 and 7. (b) Reconstruction of the image obtained with the prototype.

After checking the functionality of the prototype, the evaluation test was carried out. The voltage data collected after two measurements cycles for the same homogeneous medium showed a low
predisposition of the system to be affected by noise. In figure 6, graph (a) compares the behaviour of the voltage data obtained in the first and second measurement. Graph (b) shows the percentage of error between each sample measured, showing an error that does not exceed 2.6%, so that both groups of data are very similar to each other.

**Figure 6.** Graphs of two measurement cycles. (a) Comparison between the first and second cycle of taking measurements of a homogeneous medium. (b) Percentage of error between the first and second measurement cycle.

### 4. Conclusions

In this work we presented a design for a low-cost electrical impedance tomograph, highlighting each of its stages. A voltage-controlled oscillator dependent on electronic components external to the generator allows the establishment of the frequency and amplitude parameters of the reference wave for the excitation signal, the prototype allows the selection of a frequency range from 0.001 Hz to 300 kHz by modifying just some component values. On the other hand, the design of the high precision voltage controlled current source allows the modification of the amount of current injected from the value of a single resistance, in a test medium with water it was possible to generate a current of 1mApp to all excitation channels precisely. The electronic circuit proposed for generating pulses to achieve synchronous sampling allows the free displacement of the sampling moment in time, giving the freedom to measure both the real and the imaginary part of the impedance separately.

This proposal provides an alternative adaptable to the needs required for each application since it only requires the modification of the value of some components. The result of the evaluation of the sensitivity to noise by the prototype is within an acceptable tolerance range with a maximum error percentage of 2.6%, setting the precedents of a first prototype with relative precision to which design improvements can still be made.

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