

Electrical Impedance Tomography Image Reconstruction: Impact of Hardware Noise and Errors

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Abstract— Electrical Impedance Tomography is a hardware efficient alternative medical imaging method, where low AC-currents are applied to a biological medium through an electrode cluster. However, the signal acquisition can be very sensitive to current input or voltage output which further produces noise and thus errors. In this work, we examine the impact of the aforementioned which occurs in the electronic components of the system, i.e. short as well as open circuitry in electrode channels. In addition, the results of input signal SNR are also discussed. Modelling of the system is performed using LTspice and afterwards the output signals are processed via MATLAB, in order to identify and reduce noise levels.

Keywords— *Electrical Impedance Tomography, LTspice, Resistor mesh, SNR, short circuit, open circuit, contact impedance*

I. INTRODUCTION

Electrical Impedance Tomography (EIT) is a medical imaging technique which depicts the relative conductivity distribution of a surface (2-Dimensional case) or a volume (3-Dimensional case) of an object or a human tissue encircled by a cluster of electrodes. Although EIT is a much cheaper, safer and simpler method to perform in contrast with CT, MRI and Ultrasound, it lacks satisfying distinguishability and spatial resolution; something that still keeps EIT away from wide use in the application field [1].

Despite the low resolution, the continuous research progress in EIT imaging has led to significant improvement in speed and quality. The method is not reduced to the reconstruction of a raw conductivity map image, but also offers real-time information about special functionalities that cannot be easily acquired by traditional imaging techniques, e.g. lung inspiratory-expiratory and blood circulation near heart region [1], [2]. However, in order to perform the proper voltage output to conductivity mapping as well as apply image processing algorithms, an effective and almost noiseless hardware is fundamental precondition, since the EIT mathematical problem is already poorly conditioned; thus low measurement errors lead to large solution deviations [3].

The purpose of the current work is to search the permissible current signal noise limits as well as the affection of common measuring errors in the image quality. More specifically, the hardware part of the EIT system is modeled with LTspice as well as the acquisition domain as a RLC grid. Afterwards, the simulated outputs are processed digitally in order to acquire and reconstruct the final image.

This paper is organized as follows: In session II the mathematical background of the EIT problem is presented. In session III, a brief description of the simulated hardware and the measuring domain is drafted. In section IV, the measurement acquisition process is described and possible error sources are countered, while the corresponding simulations and image reconstructions are performed. Furthermore, comparisons and estimation of each problem's consequences are discussed. In the final section the conclusion is written.

II. THE EIT RECONSTRUCTION PROBLEM

Defining an area or domain of examination $\Omega \in \mathbb{R}^2$ and a boundary $\partial\Omega \in \mathbb{R}$, the quasi-static nature EIT problem can be described by the Poisson equation:

$$\nabla(\sigma \nabla V) = 0 \quad (1)$$

in Ω , where σ is the relative conductivity and V the potential. The boundary conditions are $\int_{EI} \sigma \frac{\partial V}{\partial n} ds = I_i$ and

$V_{boundary} + z_i \sigma \frac{\partial V}{\partial n} = V_i$, where i refers to the i -th electrode current insertion or voltage measurement and z is the corresponding contact impedance [1], [3]. The domain geometry is usually a-priori known (model).

A. The Forward Problem

The Forward Problem refers to obtaining the area's voltage distribution assuming a known conductivity distribution. Many ways have been proposed for that, including analytical methods limited to basic domain geometries and more flexible numerical methods [1]. The most common state-of-the-art is the Finite Element Method (F.E.M.), where the area is divided to numerous canonical shapes (elements with local and global nodes), while (1) is properly integrated. After assembling the local nodes to the global ones, a system of the following form is constructed:

$$\begin{bmatrix} A_M + A_z & A_v \\ A_v^* & A_D \end{bmatrix} \begin{bmatrix} U \\ V_l \end{bmatrix} = \begin{bmatrix} 0 \\ I^d \end{bmatrix} \quad (2)$$

where A_M has occurred from assembling the local element

matrices $A_m = \iint_{\Omega_E} \sigma_E \left(\frac{\partial \varphi_i}{\partial x} \frac{\partial \varphi_j}{\partial x} + \frac{\partial \varphi_i}{\partial y} \frac{\partial \varphi_j}{\partial y} \right) dx dy$, A_z from

$A_z(i, j) = - \int_{\partial\Omega_E} \varphi_i \frac{1}{z_l} \varphi_j ds$, A_v from $A_u(i, j) = \int_{\partial\Omega_E} \frac{1}{z_l} \varphi_i ds$ and

A_D from the $A_d(i, j) = \begin{cases} \frac{1}{z_i} |E_i|, & i = j \\ 0, & \text{elsewhere} \end{cases}$ local matrix. It is also

noted that Ω_E is the element domain, E_i each electrode's length, $\bar{\sigma}_E$ the element's average conductivity, ϕ potential and i, j refer to the corresponding nodes. U are the global nodes potentials and V_i the electrode potentials. The system (2) was used to be solved with the Cholesky method in the past; however, the conjugate gradient one has been proved more fast and accurate [3]. After obtaining the voltages, linearization around a background conductivity σ_{ref} is performed:

$$J_{ij} = \left[\frac{\partial V(I_i^d)}{\partial \sigma_{ref j}} \right], \quad J \in \mathbb{R}^{mxk}$$

where k is the system's degrees of freedom, and m is the total number of measurements [3]. This matrix is called Jacobian or Sensitivity, since each row maps the corresponding current-voltage measurement sensitivity in the interest area.

B. The Inverse Problem

The EIT inverse problem is concisely described by the search of the conductivity distribution, knowing the domain's potential for each current-voltage stimulation. It is actually the solution process of the linearized system $J(\sigma - \sigma_{ref}) = V_i - V_{ref}$ where σ is the unknown conductivity, σ_{ref} the reference conductivity, V_i the voltage measurements and V_{ref} the estimated (or measured) reference voltages. This system is always severely ill-conditioned, which means that its singular values tend exponentially to zero. As a consequence, low noise disturbances in potential cause large damage to the solution [3].

The problem is dealt with an added regularization term, which balances the ratio between $\|J(\sigma - \sigma_{ref}) - (V_i - V_{ref})\|$ and $\|\sigma - \sigma_{ref}\|$. The generalized solution is given by [3]:

$$\sigma = \sigma_{ref} + (J^*WJ + \lambda^2 R)^{-1} J^*W(V_i - V_{ref}) \quad (3)$$

where $W = \text{diag}(\text{cov}^{-1}(V_{ref}))$ (for non-normalized measurements) or $W = I$ (for normalized measurements) when contact impedances are equal, λ the regularization parameter and R a prior (in actual this amplifies the diagonal terms of J^*J to make it reversible). Many priors have been developed for that purpose, such as Standard Tikhonov ($R = I$), NOSER ($R = \text{diag}(J^*J)$), etc. In addition, iterative methods based on this generalized solution have been proposed and used (Gauss-Newton, etc.), especially when conductivity disturbances are large-contrast to the background and the Jacobian linearization is inadequate.

III. HARDWARE SETUP

An EIT system usually includes a sinusoidal current source (up to 1mA, 10kHz-100kHz), two analog de-multiplexers for the current injection to the electrodes, two analog multiplexers for the differential electrode potentials, low pass filtering (DC-cut-off) of the voltage outputs, an instrumentation amplifier, an ADC and a microprocessor unit to control the circuit

functionalities. Many different EIT systems have been developed, with some of them already being used in the application field [2]. However, a relatively accurate prediction of the behavior of an under design system remains challenging, due to lack of examination domain models compatible with circuitry simulators. Some efforts to discuss the behavior of an EIT system under external disturbances are reduced to theoretical analysis, the-important-factor of electrode positioning, a single analog front-end channel or the digital part (sampling errors). [4], [5].

In this work, we used a feature of the EIDORS library tool of MATLAB, which transforms a F.E.M. model mesh to a LT spice file that includes the equivalent resistor network [6]. An extended description of the association between the F.E.M. and the resistor mesh can be found in [7].

In this paper, a 16-electrode system was simulated, using the adjacent pattern [8]. ADG426 analog multiplexers were chosen, characterized by a wide-range supply voltage ($\pm 15V$), 80 Ohm resistance and very fast switching times ($\sim 160ns$). A first order low pass filtering at 200Hz was used in both differential outputs, along with an AD8421 Instrumentation Amplifier. In previous EIT implementations, the current source was usually implemented by a voltage output DDS and DAC, followed by a Voltage-to-Current Converter (VCCS); however, a less hardware cost and less-noisy solution is the usage of current output DACs, especially in this case that current amplitude is low enough. Thus, the current source is presented almost ideally, with a large resistor in parallel connection, and a noise source. The SNR of the input signal is clearly affected by the DAC's SNR, and that could be increased with oversampling (>10 times the current frequency), resulting:

$$SNR = 6.02L + 1.72 \text{ dB} + 10\log_{10} OSR \quad (4)$$

where L is the number of the DAC's bits and OSR the oversampling ratio. Thus, a low-noise, high sampling and at least 16bits DAC is highly recommended, in order to achieve a current SNR of more than 90dB [9].

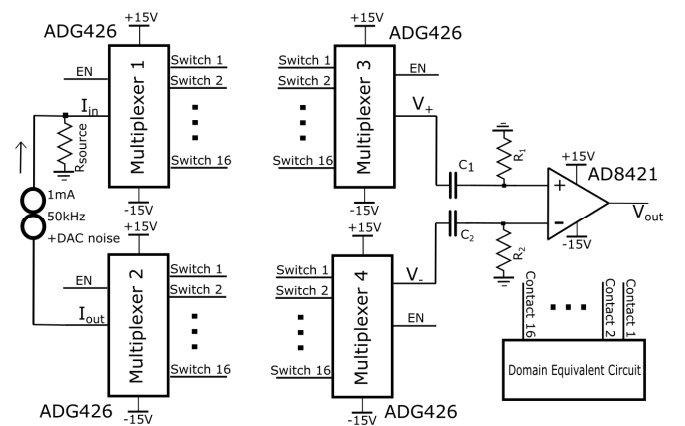


Figure 1: Schematic of the EIT system implemented on LTSpice

The electrode lead wires and their contacts play a significant role in the hardware's efficiency. To examine their affection, the electrode models were also implemented in LTSpice, as shown in Fig. 2 [1].

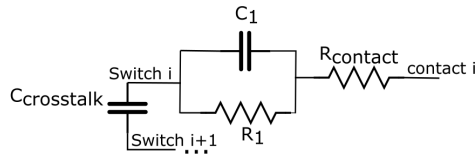


Figure 2: The electrode equivalent model used on LTspice. Crosstalk capacitance between the lead wires was also included.

IV. SIMULATIONS AND RESULTS

Some common error cases were simulated and examined. With the assistance of the EIDORS library tool, a forward model was designed, including 3 circle conductivity perturbations in a circular domain, encircled by 16 equally distanced small-dimension electrodes, as shown in Fig. 4a. The background conductivity was set to 1Sm^{-1} while each perturbation was set to 0.9Sm^{-1} . The conductivity changes ($\Delta\sigma$) are only 10%, thus, one step linearized reconstruction algorithms can be effectively used. The input domain was firstly transformed to an equivalent resistor circuit with 16 nodes, imported into LTspice. Then, LTspice simulation is performed and a voltage output file is exported.

In order to get the final voltage measurements, effective sampling of integer periods of the output signal have to be performed. Each measurement begins after steady state has been established and stops before the multiplexers switch to the next state, as shown in Fig. 3. It is obvious that higher input signal frequencies and lower channel capacitive effects allow higher fps rates, provided that a high enough performance and SNR ADC is used. The noise levels of an ADC are calculated in the same way with the DAC. In this simulation case, the output signal file was acquired from LTspice and transferred to MATLAB in order to isolate the final voltage amplitudes according to the formula described. However, since LTspice itself outputs digital signals with high sampling rates (MHz), the ADC function was not precisely simulated.

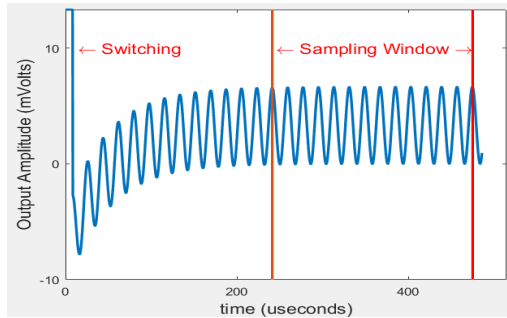


Figure 3: Indicative plot of how amplitude measurements are taken

At first, it is assumed that the EIT system is well-working with a DAC and an ADC SNR rate of 90dB where all crosstalk capacitances and electrode contact impedances are equal (30pF and 100ohms respectively). For the inverse image reconstruction, the NOSER prior was used with $\lambda=0.003$ and a mesh of 2304 elements and 1573 nodes. The conductivity perturbations are satisfactorily reconstructed, demonstrated in Fig. 4b and can easily be distinguished. Since the inverse problem does not have a unique solution, the actual conductivity values cannot be precisely computed and usually arbitrary units are displayed to express the relation between each element's conductivity (negative values are a very frequent case). Nonetheless, a-priori information about the approximate conductivity values of the materials examined can be utilized to properly map the computed values to the known absolute ones.

Simulations of short-circuit cases between electrode channels 2-3 and 2-9 were implemented, with the results displayed in Fig. 4c and 4d. In the first case, when current source is far from electrodes 2 and 3, the voltage signal from both electrodes is obviously the same, resulting in very low displayed resistance between 2 and 3 in Fig. 4c. When multiplexers switch currents, from electrodes 2 and 3, actually the current source is neutralized due to very low load impedance and almost no voltage signal is measured. When current is inserted from electrode 1 or 3, current flow is divided to electrodes 2 and 3, leading the measurements to saturation. Although malfunctions cause critical errors to the final image, the error is detectable from high conductivity paths between short-circuit electrodes.

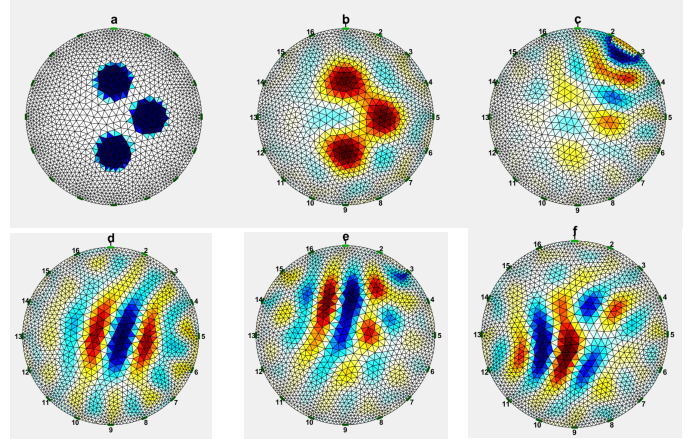


Figure 4: Desired image and NOSER reconstructions for the following cases: b: high SNR circuitry, c: short circuit between electrodes 2-3, d: short circuit between electrodes 2-9, e: disconnected electrode 1 and 10, f: disconnected electrodes 1 and 10. Intense colours in reconstructed images indicate higher impedance (arbitrary values), contrary to blue type colours. The electrodes are numbered on the circle peripheral.

Another frequent error case is a disconnected electrode from the whole circuitry, most likely due to a high impedance contact or an open circuit leading wire. Afterwards, when a current source is connected via multiplexer switching to this electrode, no current is able to pass since the load impedance is almost infinite. Otherwise, when measuring voltages, the disconnected electrode remains a floating point, leading to erroneous measurement, i.e. saturation. Test cases for disconnections on the 1st and the 1st in addition with the 10th channel were executed. Results are shown in Fig. 4e and 4f respectively. The perturbations are not successfully detected. Nevertheless, modifying the covariance matrix W (inverse problem algorithm), we are able to cancel the measurements correlated with the erroneous electrode; reducing the available data along with the imaging failure.

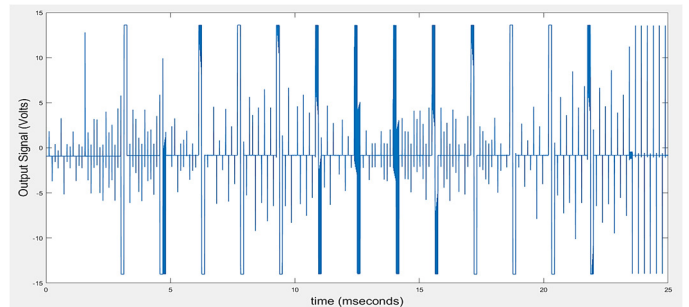


Figure 5: Voltage outputs of a full measurement cycle as simulated in LTspice when lead wire 1 is open-circuit. Saturation is occurred when measuring from the corresponding electrode (floating-voltage).

Furthermore, a comparison of EIT imaging quality is presented for various current signal noise levels, specifically for 60, 30, 20 and 12dB. That Gaussian noise derives from quantization noise of the DAC and the ADC in addition to the analog VCCS circuitry noise if used. It is reasonable that every analog circuitry added to the path between the produced waveform and the electrode contact, or the voltage electrode and the ADC, severely reduces the SNR, especially if traditional current sources (e.g. Howland topology [9]) are implemented. The results are shown in Fig. 6 and indicate that a reliable reconstruction is obtainable until 25-30dB. However, the output signal SNR is expected much lower, since noise will be certainly produced by the analog part. Thus, an input signal SNR of more than 60dB would be desirable and could succeed with an all-digital signal generator.

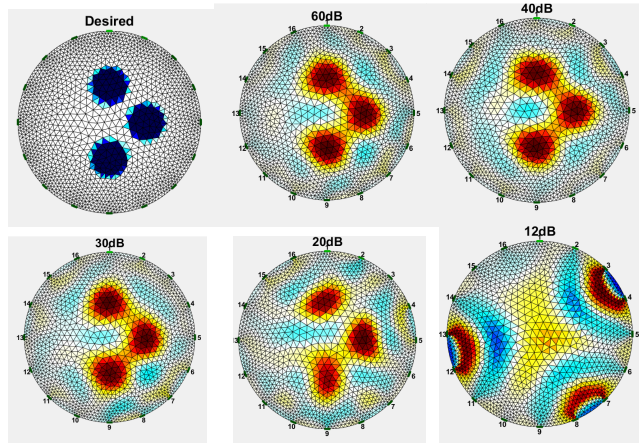


Figure 6: EIT NOSER image reconstruction for some current SNR values

Another simulation is implemented in order to detect the impact of changes on the electrode contacts, assuming random variations of 1 to 10 Ohms and 10 to 50 Ohms. The results in Fig. 7 show that lower trace or contact resistance variations between the channels lead to a more successful reconstruction. That occurs because the contact impedance is in series with the impedance of the domain measured; thus all contact impedances have to be as smaller and nearer as possible. A calibration circuit and modifications in A_z , A_u and A_d matrices (see forward model) might be a proper solution; along with careful design of the analog front ends. In addition, in medical application of EIT, gel is used between the electrodes and the skin reducing the contact impedances as possible.

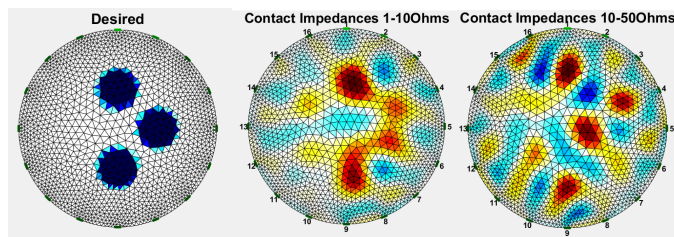


Figure 7: Image reconstruction of the desired domain for various contact impedance ranges.

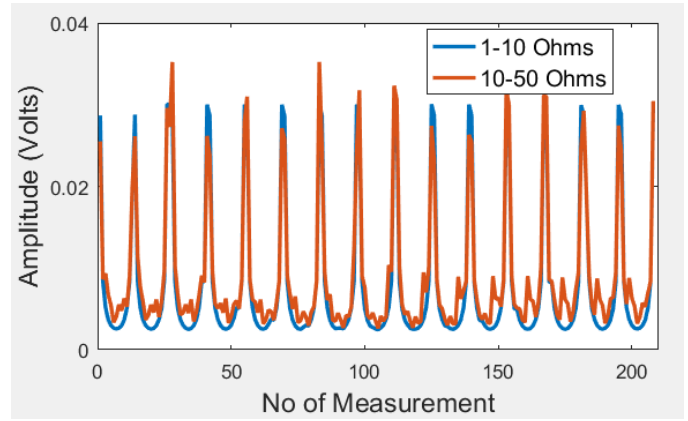


Figure 8: Differential voltage measurement amplitudes when the channel and contact impedances vary from 1-10 Ohms and 10-50 Ohms.

V. CONCLUSIONS

Simulations show that short and open circuits in the EIT channels cause critical image errors. In addition, the output signal noise levels are affected by the quantization noise of the DAC and ADC. Furthermore, contribution of the front ends non-idealities lead to the requirement of a careful analog part design. Moreover, the efficiency of an EIT system is directly depended on the electrode channel traces and contact impedances that must be limited and closer to each other as feasible.

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