Electrical Impedance Tomography image reconstruction using backprojection with OpenCV

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Abstract. In this work is presented a graphical user interface implementation for imaging Electrical Impedance Tomography by Sheffield backprojection. C language is used and the OpenCV library is implemented to display a tomographic image with color levels according to the conductivity level in the studied medium. This implementation is presented as an alternative for electrical impedance tomography imaging using filters and colormaps without Matlab software. Some real data reconstructions were made to validate the correct operation and the resolution of the image was improved using filters.

Keywords: Electrical Impedance Tomography, OpenCV, Image reconstruction, Sheffield backprojection

1 Introduction

Actually the Electrical Impedance Tomography image reconstruction is made with a specialized software called EIDORS: *Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software* that is free and open source. Despite these advantages, it is required to have installed a Matlab version (or Octave) to use all its features. The hardware that collects the measured data to reconstruct a tomographic image can be adapted to Matlab, and it is possible to generate a data output necessary to image a conductivity distribution. Nowadays, the most used output is an image formed by a finite number of pixels. A compiled specific software for some specific application of Electrical Impedance Tomography (EIT) is more practical because in this way the involved algorithms that solve direct and inverse problems can be easily manipulated from code. As a result it is possible to access to numerical values of conductivity or other variables of interest. This paper seeks to deploy tomographic images in a user-friendly interface through an OpenCV library as an easy and highly efficiently alternative. A colormap that gives contrast is displayed to differentiate conductivity values too.

1.1 Electrical Impedance Tomography

Electrical Impedance Tomography (EIT) is a technique that can produce images distribution of admitivity, or electrical conductivity, of electrically conductive objects by injecting known amounts of current, and measuring the resultant electric field at the surface of the object [1,2].

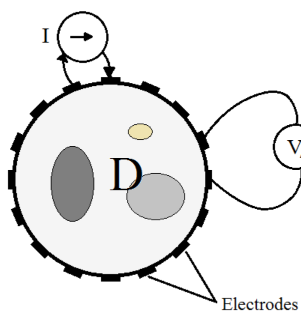

Fig. 1: Configuration of the current injection and potential measurement in EIT

In Fig. 1 is shown the typical configuration for the reconstruction problem in two dimensions, it consist of a 16 electrodes array placed on the surface of the region D. A pair of electrodes is used to inject a sinusoidal current I inside the object; the resulting potential distribution is measured pair by pair in the remaining electrodes. These measured voltages are denoted as V_l. After this is done, the procedure is repeated by injecting the current to the next pair of electrodes and measuring the new potentials. In this way,16 times the current injection it will be made until to complete a round, thus having a vector of 208 measurements potential difference between the electrodes on the surface of the object. A vector of measures, corresponding to 16 measurements of 13 potential values between the electrodes attached to the surface D of the object being studied, will have stored.

The governing equation in EIT is

$$\nabla \cdot (\sigma \nabla \phi) = 0 \in D \tag{1}$$

where σ represents the conductivity and ϕ represents the potential inside the region D.

This is the Laplace equation for the linear case, a second order partial differential equation and elliptical. For this two dimensional problem only the coordinates x and y are considered.

This equation models the flow of the electric current across the medium in region D, as it represents the divergence of the gradient for the potential ϕ. In this particular case, it measures the amount of electrical current flowing in and out of the region D in a circular form, typically used in EIT.

In another particular case, when the Laplace equation has conductivity $\sigma = k$, with $k = 1$ or a constant we are treating with an homogeneous medium where the same amount of current into one of the electrodes is exactly the same coming out, fulfilling the same but for a nonlinear governing equation case when using Poisson equation is modeled.

1.2 Polar and adjacent current injection

Two of the most commonly used methods for injecting current in EIT are the adjacent method method and the polar injection. The adjacent injection method applies the current between two adjacent electrodes (neighbor electrodes), and the potentials are measured in the remaining adjacent pairs of electrodes. This process is repeated until each one of the possible adjacent pairs have had an injection current [3]. This method is too sensible to conductivity contrasts near the boundary, and it is insensible to central contrasts. The polar injection (opposite electrodes), mainly used in brain EIT, applies a current to a pair of electrodes that are opposite 180 each other while the potentials are measured in the remaining pairs of electrodes. Polar injection strategy suffers the disadvantage that for the same number of electrodes, the available number of current injections that can be applied is lower than in the adjacent strategy. In this work is used the adjacent type current injection, since a total of 208 measurements of potential are required to enter the program and use the backprojection.

1.3 EIT image reconstruction

Electrical Impedance Tomography image reconstruction has been studied with static and differential techniques. Static reconstruction use a data set to carry out the reconstruction while differential reconstruction uses two data sets and computes a conductivity difference [4]. There are different reconstruction techniques, as the linear backprojection, Newton-Raphson method, Graz Consensus Reconstruction Algorithm (GREIT) [5,6] and the conjugate gradient method [7] to name the main. In this paper is used the linear backprojection technique by equipotential lines, also called Sheffield backprojection [8], which is a type of differential reconstruction. Several of these methods as well as solvers of the forward problem are included in the EIDORS software [9].

1.4 Linear Backprojection

The backprojection method is a reconstruction method widely used for imaging EIT. In Electrical Impedance Tomography, it is required to make a modification of the conventional backprojection in order to use this technique. In EIT the straight lines strategy cannot be used because changes in all elements of the object affect the measurements. After all current patterns are applied, the projected values are summed to obtain a value for a pixel. The algorithm is then [10]

$$\frac{\delta\sigma}{\sigma} = B\frac{\delta V}{V} \tag{2}$$

where B is the backprojection matrix. The lines used for the backprojection are the equipotential lines in each current injection since for the given element, the maximum sensitivity measured can be found at the intersection of the boundary and the line from the element. The equipotential lines are unknown due to the unknown conductivity, therefore they must be approximated. Usually the approach is based on the assumption that the object is circular, and it has a constant conductivity. There are different versions of the backprojection algorithm, one of the most used is the proposed by [11]. In this work is used the Sheffield backprojection matrix [12]. The reconstruction by backprojection presents a fast computing, since only multiplications are processed. The current injection technique for this case will be by adjacent electrodes.

2 Methodology

The methodology to obtain the internal conductivity of a region using EIT is proposed as follows:

First an electric current is injected and measurements are taken by some method, such as adjacent injection, readings of potential are taken between the remaining pairs of electrodes and the lectures are stored in a vector or a matrix for later use. Once the measured potential values are obtained, these must be entered into the program for the processing; as backprojection is used, it is necessary to have potential measurements made in a homogeneous medium and also measurements in a disturbed medium. In this case the measurements of the disturbed medium are the real measurements from the measured region. Subsequently backprojection is applied to obtain a vector that represents the conductivity values σ of finite small elements within the studied region. A distribution which can be represented by an image of pixels with a given color scale values of conductivity is obtained.

For the first stage, measured data is simulated with the potential values computed in the most widely used software for EIT called EIDORS (Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software [4]), if desired, you can also to perform the current injection via hardware, but in this case only examples with preset values are explained. For the second stage the backprojection matrix B is used, whose values have been calculated by [12]. The implementation of the backprojection matrix in the program is done in C language to reconstruct the distribution of conductivity values according to the equation (2). For this, a dialog box is implemented in *Windows Forms* from Visual Studio and a tool type *PictureBox* is added. Behind this object, the presentation of the conductivity values calculated in backprojection will be programed. OpenCV is used to generate a gray scale or a list of colors for the color generation. The shape of quadrilaterals, the size and the outline of each of these parts are also considered tracing quadrilaterals that represents a matrix of pixels. First the deployment of a reconstructed gray scale image is made and finally an example is displayed with colors. The used colormap can be variable, being a standard the gray scale and the colormap configuration for *Jet*. Finally an image (32×32 pixels of low resolution) that can be filtered by the same OpenCV library is generated, and for this work a Gaussian filter is used.

3 Results

The graphical user interface was created using a Windows Forms application with Microsoft Visual Studio, in this part the operations relating to the equation (2) are programmed. First is calculated

$$V_e = \frac{V_{meas} - V_{ref}}{V_{ref}} \tag{3}$$

that computes the operation for obtaining $V_e = \frac{\delta V}{V}$, and thus obtain [11]

$$\sigma_e = B_{_M} \cdot V_e \tag{4}$$

where $\sigma_e = \frac{\delta\sigma}{\sigma}$. The linear system that is typed into the compilator is then represented as

$$[\sigma_e]_{912\times 1} = [B_{_M}]_{912\times 208}[V_e]_{208\times 1} \tag{5}$$

and σ_e represents a conductivity vector containing the values of each discrete element in which the measured region is divided, $B_{_M}$ is the backprojection matrix and V_e is the measured potential between electrode pairs in all projections by adjacent injection current.

For the graphics, a total of 16×13 potential measurements will be taken, and with the matrix $B_{_M}$ a total of 912 pixels will be taken with conductivity values represented by a color value. To adapt the pixels to a circular image, some values are ignored and are deployed only 856 values in the computer screen.

To display an image, first a homogeneous medium is selected, the values of potential are calculated by solving the forward problem in EIT and potential values are stored; after, a medium is taken with an object with known conductivity within. In this case, a phantom was taken from the software EIDORS [13]. In the Fig. 2 is shown an example from EIDORS, where two objects are known, the first one with a conductivity value of 1.1 (*left perturbation*) and 0.9 (*right perturbation*). This software allows to show the conductivity values computed after to solve the inverse problem in EIT and the Fig. 2 shows the output in the right part. Once the solution for calculations of $\delta\sigma$ in C language

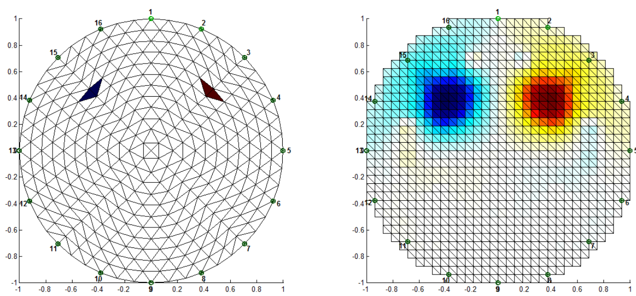

Fig. 2: Example with two perturbations inside a circular region and the conductivity equivalent after the solution with EIDORS

is implemented, we will have a vector solution of 912 elements. In order to display them on a screen with a color scale, it is necessary to use the library OpenCV. A total of 856 quadrilateral pixels in a 32×32 size screen are displayed. Some of the pixels are not considered for displaying because of the imaging of a circular area and placing white color instead of a color of the conductivity value. In the first implementation, it was used only a gray scale for imaging reconstructed by backprojection. Fig. 3 shows a reconstructed image using the same values computed in the forward problem obtained by EIDORS, it can be noticed that this is the same image since the results of conductivity in each element agree totally. Up to this point the OpenCV library was only used to draw the pixels of the backprojection reconstruction, using drawing functions as *cvRectangle();* for filled pixels with a RGB conductivity value and for the outline of each pixel. Later the OpenCV library was used to improve the presentation on the deployment of the image, adding color to the interface with some features such as the application of a colormap, drawing of a colormap value bar, filtering and generation of multiple images at the same time on the screen.

To validate the obtained results reconstructing an image, a sample was taken and the images were reconstructed in both EIDORS and the developed program. This is an example that contains an object near the center in a circular region. Fig. 4 shows the reconstruction results. Qualitatively it is possible to observe that it is the same object, it must be noticed that since the image is in a gray

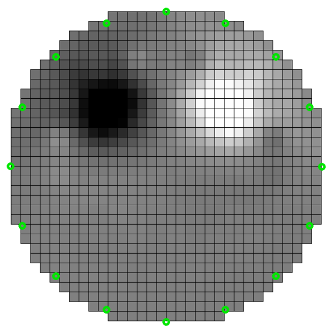

Fig. 3: Backprojection using an interface with C language and a gray scale

scale, it is not possible to make a hard comparison and is required to perform the same reconstruction using colors to highlight contrast and values of specific conductivity in certain regions. The results using colors are shown later in this work. To check the operation of reconstruction with real measurements, some

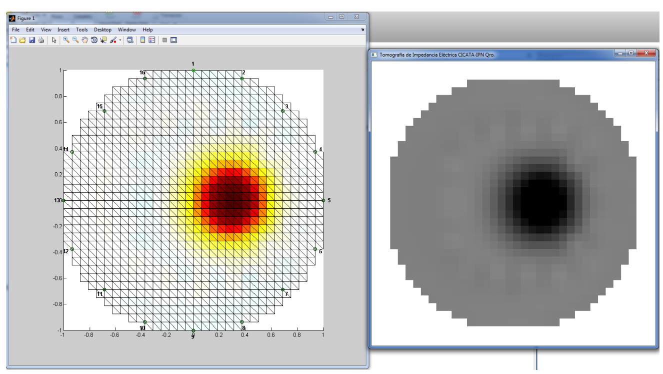

Fig. 4: Comparison of the image output using EIDORS and using the developed interface

real measured data were taken from a test phantom and made at the University of Ottawa in October 2005 [14]. The data were taken in an experiment of a 30cm diameter circular tank with a saline solution of 0.9% and a non-conductive spherical object inside, then the same experiment was performed with two non-conductive spherical objects. The non-conductive object is a golf ball 2cm radio.

In Fig. 5 are shown both reconstructions with the program, in the first one, an object is located at (-7,0) cm (*left*) and in the second one are shown two objects, one at (0,7) cm and other at (-7,0) cm (*right*). In Fig. 5 you can notice a

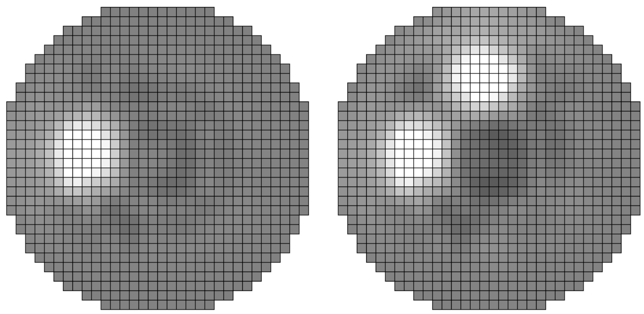

Fig. 5: Real image reconstruction with measurements made in a phantom, *left:* a Golf ball, *right:* two Golf balls

low resolution in the generated image but a high contrast. That is a distribution of the conductivity of a saline solution versus the conductivity of the object, in this case non-conductive; the high contrast highlights shows non-conductive regions like the golf ball clearly, it makes this technique very useful in detecting possible applications as *in vivo* bone density applications.

Once having these results, we proceed to improve the interface, a stage was added into the program that will add color to the grading scale conductivity values. It is a color graduation equivalent to type *jet* colormap. Fig. 6 shows the backprojection reconstruction of the first example with a color scale. In this case the pixel grid appears defining the size of each pixel.

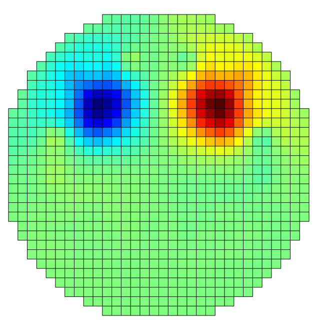

Fig. 6: Backprojection using the equivalent colormap *jet*

The color assignment is performed directly in the program by calculating some numerical values, working in color levels (R, G, B). For gray scale, the allocation is as follows:

```
cc=0.5-data[ ]/2;
r=cc*255;
g=cc*255;
b=cc*255;
```

with cc a *double* type variable and r, g, b *integer* type variables. cc must be a vector with values in 0 and 255. For the color scale, the next assignment must be used:

```
cc=2*(0.75 - abs(data[ ]));
if(cc>1) cc=1;
if(cc<0) cc=0;
g=cc*255;
cc=1.5 - 2*abs(data[ ] + 0.5);
if(cc>1) cc=1;
if(cc<0) cc=0;
r=cc*255;
cc=1.5 - 2*abs(data[ ] - 0.5);
if(cc>1) cc=1;
if(cc<0) cc=0;
b=cc*255;
```

This for the case of *jet* assignation, where *abs* denotes the absolute value of *data[]-0.5*. For any other color scale, simply must be programmed an assignation based in function of *data[]*, that is the vector containing the values of conductivity after reconstruction.

It is worth mentioning that the interface has the ability to read 208 values of difference potential from the electrode pairs placed on the boundary of the region that is measured. Thus the acquisition of potential is a vector of 16×13 values, since the system was designed for a connection of 16 electrodes, thus a potential vector of readings on the boundary is defined

$$m_{rec} = \left\{ \begin{array}{c} [v_1^1, v_2^1, \cdots, v_{13}^1]^T \\ [v_1^2, v_2^2, \cdots, v_{13}^2]^T \\ \vdots \\ [v_1^{16}, v_2^{16}, \cdots, v_{13}^{16}]^T \end{array} \right\} \quad (6)$$

where v_i^j is the i-th measurement in the j-th injection. With this information is possible to solve quickly the equation (5) for σ_e.

An improvement that can be done is the implementation of a Gaussian filter, using the *GaussianBlur()* function which is included in the openCV library. Filter parameters applied were the standard deviation kernel address $x = 51$ and the standard deviation $y = 51$.

Fig. 7 shows the interface with *jet* colors and the Gaussian filter applied. The smoothing is chosen arbitrarily in this case, but with lower values than here proposed, results do not distort the image. For this filter are always required

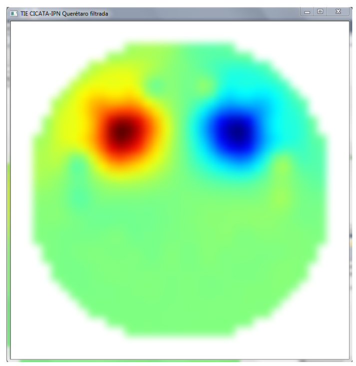

Fig. 7: EIT reconstructed image and filtered using OpenCV

the standard deviation kernel parameters as odd or possibly zero, with the instruction to C ++ language:

```
cv::GaussianBlur(<input array>, <output array>,
kernel size(51,51), border type=0);
```

It is possible to use this information for further analysis of conductivity in regions that show contrast, for example, an application in the future of this work, is the density detection by image, also can be used for forms detection, seeking malformations or for application in other involving Electrical Impedance Tomography.

4 Conclusions

The Sheffield backprojection method for imaging EIT was implemented successfully without using EIDORS and Matlab, instead of this, were used C language and the OpenCV library with the possibility to apply a Gaussian filter and the jet colormap; the image was reconstructed into a level of conductivity values represented by colors, thus we have a friendly graphical interface that displays an EIT image. The reconstruction was made from 208 potential measured values using Sheffield backprojection. Some reconstructions of real data were made to validate and display a color filtered image with contrast.

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