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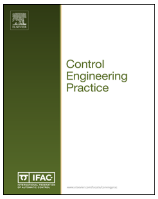

Influence of current injection pattern and electric potential measurement strategies in electrical impedance tomography

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ABSTRACT

Electrical Impedance Tomography (EIT) is a non-invasive image reconstruction technique, whereby current is injected by electrodes and electric potential is measured by electrodes. In some electronic hardware implementations, only two electrodes inject current simultaneously, and are denominated pair-wise current injection. Several possibilities of pair-wise current injection (electric current patterns) and electric potential measurement (single-ended and differential) have been addressed in the literature. Considering pair-wise current injection, the *skip-m* current pattern can be defined as a pair-wise injection strategy in which the number of non-current injecting electrodes enclosed between two injection electrodes is *m*. Single-ended electric potential measurements consist of measurements with a common potential reference. Differential electric potential measurements consist of pair-wise measurements between two electrodes. A theoretical analysis based on control theory is presented to show that some current and measurement pattern strategies convey less information than others. This hypothesis is verified by the analysis of the matrix containing possible measurement vectors, with respect to its rank, condition number and singular values. Additionally, a novel approach is proposed to analyse current and measurement patterns based on uncertainty estimation of difference images by the correlation matrix linearization of the reconstructed impedance matrix. The results show that single-ended potential measurements are usually better when compared to differential electric potential measurements. A conclusion supported by both points of view is that the cross current pattern (diametral) is the least informative for these symmetrical domains.

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1. Introduction

Electrical Impedance Tomography (EIT) is a non-invasive image reconstruction technique of the impeditivity distribution in which current is injected through electrodes and electric potential is measured by electrodes. EIT images can be classified as absolute images and difference images. Absolute images are those composed of impeditivity values within the domain of interest (Moura, Aya, Fleury, Amato, & Lima, 2010). Difference images are those composed of variations in impeditivity values with respect to a reference impeditivity distribution. The reference impeditivity distribution is usually employed as a linearization point for the nonlinear set of equations representing the electric potential within the domain. Absolute images are prone to present artifacts due to modelling errors, such as boundary shape, electrode position and contact impedance mismodelling. Difference images are more robust for such modelling errors (Adler et al., 2012, Adler, Grychtol, & Bayford, 2015). The reason is that difference images are obtained from subtracting measurements. By proceeding this way, many modelling errors are attenuated during the subtraction operation, whereas algorithms for estimating absolute images do not have the same privilege. On the other hand, using a difference image scheme, any pre-existing conditions within the domain at the time of acquiring the reference measurements will normally be hidden from the difference image, unless multifrequency or functional information is added. Absolute images may reveal

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conditions of clinical interest; they may discriminate pleural effusion from atelectasis (Nebuya et al., 2015), detect pneumothorax occurrence (Leite et al., 2008), and allows continuous monitoring of lung conditions during mechanical ventilation (Costa et al., 2009).

Some electronic hardware implementations, in which only two electrodes inject current simultaneously, are often denominated pair-wise current injection. There are several ways in which the pair of electrodes is switched and the electric potential measurements are collected. Let m be the number of non-current carrying electrodes between the pair of injecting electrodes. If this number is fixed for all possible choices of pairs of injecting electrodes, it is denominated as $skip - m$ current pattern. Brown and Seagar (1987) suggested a method whereby the EIT equipment with 16 electrodes sequentially applies an electric current to the body using a pair of adjacent electrodes (called $skip - 0$ current pattern herein). While the current is applied, electric potentials are measured between adjacent non-current carrying electrodes. This procedure is repeated, by applying current between each pair of adjacent electrodes to obtain an electric potential data set. Hua (1987) and Hua, Webster, and Tompkins (1988) suggested the cross method, whereby current is injected between a pair of more distant electrodes than the $skip - 0$, and the opposite method, whereby current is injected through two diametrically opposed electrodes (called $skip - 15$ current pattern herein for 32 electrodes). A key concept for comparing injection strategies is distinguishability (Cheney & Isaacson, 1992; Cheng, Simske, Isaacson, Newell, & Gisser, 1990; Isaacson, 1986). It is a general criterion to generate optimal current patterns. For a particular domain, with a specific impeditivity distribution, distinguishability is the smallest conductivity change that can produce changes in the measured electric potentials larger than the uncertainty level of the measurements in the electrodes.

Several authors separately analysed the effects of current injection and the potential measurement in the final image. Xu et al. (2008) used an EIT equipment with 16 electrodes and they compared three angular distances between the pair of injecting electrodes: 22°, 158° and 180°. They concluded that, among the three, the best angular distance between the pair of injecting electrodes is 158°. Zhang and Wang (2010) compared several current injection patterns and concluded that the best angular distance between the pair of injecting electrodes is 158° for 16 electrodes. Lionheart, Kaipio, and McLeod (2001) and Demidenko, Hartov, Soni, and Paulsen (2005) considered multiple current sources and determined the optimal current pattern. Kaipio, Seppänen, Voutilainen, and Haario (2007) addressed the observation of moving fluids through a pipeline and Yamaguchi, Katashima, Wang, and Kuriki (2013) addressed the observation of human abdominal fat using electric potential measurement patterns.

Kyriacou, Koukourlis, and Sahalos (1993) investigated bipolar current sources and found the best angular distance between the pair of injecting electrodes when one does not know the position of the disturbances within a circular area. In the same work, the authors determined the best distance considering that (i) the whole area has the same probability of containing an abnormality and (ii) the average of the best angular distance between the electrodes for all points of the domain will result in better sensitivity. The authors reached the value of approximately 48° in systems with 16, 32 or 64 electrodes.

Based on this brief introduction, several possibilities for current injection and electric potential measurement can be proposed and they are explained in Section 2. A new interpretation of control theory applied to EIT is presented in Section 3. In this section, the current injection is associated with the controllability and electric potential measurement with observability. A new method to estimate uncertainties associated with each $skip - m$ current pattern is proposed in Section 4. Section 5 shows the results for single-ended and differential electric potential measurements and the conclusions are in Section 6.

2. Current injection and electric potential measurement

As explained in the Introduction, current is injected to the boundary of the domain and electric potentials are measured at specific points of that boundary. In this section, the possibilities for performing current injection and electric potential measurements are explained. Some EIT hardware implementations inject current through a pair of electrodes, using single current source (Martins, Camargo, Lima, Amato, & Tsuzuki, 2011; Martins & Tsuzuki, 2013; Trigo, Lima, & Amato, 2004). Some authors propose current injection through multiple electrodes (Demidenko et al., 2005; Lionheart et al., 2001), requiring multiple current source calibration, which is a complex task.

In practice, the equipment is limited to a finite number of electrodes, which imposes a limit on the amount of information obtained for the estimation. Thus, it is appropriate to define what is referred as $skip - m$ current pattern and $skip - p$ measurement pattern. The present work admits a single current source and a pair-wise current injection, in which current source and ground are separated by m electrodes.

There are two strategies for electric potential measurement: differential and single-ended. In differential strategy, electric potential is measured between a pair of electrodes separated by p electrodes. Differential measurements have the advantage of attenuating common mode electromagnetic and electrostatic interferences; they present reduced dynamic range, while single-ended measurements do not suffer from a loss of precision due to a non-zero common-mode amplifier gain (Holder, 2004). This electric potential measurement strategy will be called $skip - p$ measurement pattern. In single-ended measurements, all the electric potentials are measured with respect to a common potential reference. Thus, for a set of single-ended measurements, it is only necessary to specify m for the current pattern. Conversely, for a set of differential measurements, one has to define m and p for current and measurement patterns, respectively. Both single-ended and differential electric potential measurement strategies are considered herein.

Fig. 1 depicts a $skip - 3$ current pattern and $skip - 3$ differential measurement pattern. This work considers a total of 32 electrodes and, due to the symmetry, only $m, p \in \{0, \ldots, 15\}$ will be considered.

2.1. Differential measurements

The discretized Dirichlet–Neumann map is composed of

$$\boldsymbol{K}(\boldsymbol{\sigma})\boldsymbol{\phi}_{se,i}^{m} = \boldsymbol{j}_{i}^{m}, \tag{1}$$

where $\boldsymbol{K}(\boldsymbol{\sigma}) \in \mathbb{C}^{n\times n}$ is the mutual conductance matrix, n is the number of electrodes, $\boldsymbol{j}_i^m \in \mathbb{C}^n$ is a vector containing the imposed current at the i-th and $(i+m+1 \bmod n)$-th electrodes ($skip - m$ current injection pattern), and $\boldsymbol{\phi}_{se,i}^{m} \in \mathbb{C}^n$ is a vector containing single-ended electric potential measurements at each electrode.

It is easy to note that vector $\mathbf{1} \triangleq [1\ 1\ \ldots\ 1]^{\mathsf{T}} \in \mathbb{R}^n$ belongs to the kernel of matrix $\boldsymbol{K}(\boldsymbol{\sigma})$, since the same electric potential in all electrodes does not induce any current to flow through the electrodes. This is the only non-zero vector that belongs to the kernel. Therefore, the space of expected single-ended measurements lies in $\mathbb{C}^{n-1}$.

Differential measurements can be conceived as an additional transformation of the measurement vector by employing a

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