Bartosz SAWICKI, Tomasz GRZYWACZ

Warsaw University of Technology

Electrical Impedance Tomography through an ambient fluid as a solution for electrode contact problem

***Abstract**. In this paper we introduce a new approach to impedance tomography where contact electrodes uncertainties is eliminated by immersing unknown object in the known fluid. Optical methods are used to determine the external shape of the object. The shape and known conductivity of the ambient fluid build a priori knowledge which is incorporated into the inverse algorithm method.*

***Streszczenie.** W artykule został przedstawiony nowy rodzaj tomografii impedancyjnej, w której niepewność pomiaru związaną z kontaktem elektrod wyeliminowano poprzez zanurzenie badanego obiektu w płynie o znanych parametrach. Zewnętrzny kształt obiektu został rozpoznany przy pomocy metod optycznych. Kształt obiektu oraz znana konduktywność płynu stanowią wiedzę 'a priori', która została wykorzystana w algorytmie rekonstrukcji struktury wewnętrznej obiektu. (**Tomografia impedancyjna poprzez warstwę płynu jako rozwiązanie problemu elektrod**).*

Keywords: EIT, optical tomography, contact electrodes
Słowa kluczowe: tomografia impedancyjna, tomografia optyczna, elektrody pomiarowe

Introduction

Since its introduction in 1978 [1] Electrical Impedance Tomography (EIT) appeared to be a promising modality for imaging of the human body. It is potentially inexpensive, fast and safe for patients. However, its practical deployment has been hindered by many technical and algorithmic challenges. One of them is a problem of skin-electrode contact. It is difficult to ensure reliable and stable contact between electrode and the skin [2]. Moreover precise location of the electrode could be also an issue.

In this paper we propose an extension to the classical EIT method, where investigated object is immersed in the electrode tank filled with ambient fluid. We assume that such fluid should be transparent for the light, so visibility algorithms could be deployed to determine external shape of the immersed object.

Combined Tomography

The basic idea of the proposed solution is presented in Fig. 1. On the wall of the circular shaped tank measurement sensors are located: electrodes for the impedance tomography and optical sensors for the visibility algorithms. The main reconstruction of the object is done by impedance method. Moving electrodes out of the area of reconstruction should deteriorate quality of the result. To avoid this problem we extended the method by incorporating knowledge of shape of the object and parameters of the fluid.

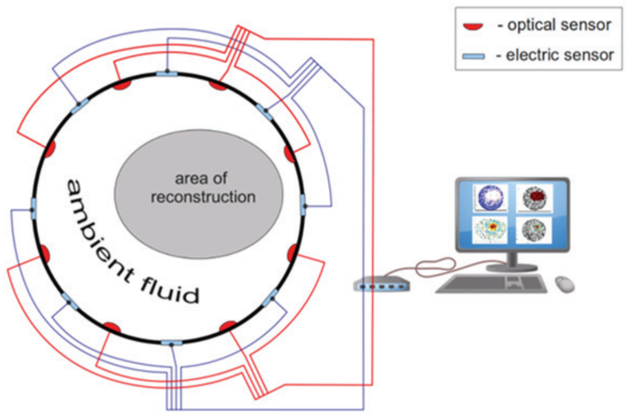

Fig. 1. Idea of EIT through an ambient fluid. Area of reconstruction is determined by the use of the optical visibility methods

Presented method could be understood as dual-modality tomography, where optical methods are combined with impedance reconstruction. Complete algorithm has several essential steps:

1. measure visibility matrix,
2. deploy visibility matrix to find external shape of the object by the help of the visual hull point-to-point method,
3. determine unknowns for the inverse problem by meshing the object,
4. perform impedance measurements,
5. solve the inverse impedance problem using Gauss-Newton algorithm with regularization.

An accurate identification of the external shape of the object allows for better imaging in EIT. The visibility matrix calculation assumes modelling of propagation of highly collimated light in non-scattering and transparent medium. Investigated object shape is obtained by inverse transformation of the visibility matrix.

The paper is based on simulated data. Both optical and electrical measurements were taken from preceding simulations. Authors are aware of risks related with such unrealistic setup. Special attention has been paid to avoid 'inverse crime' pitfall [3] by introducing noise into the signal.

Optical shape reconstruction

The most popular reconstruction approach taking into account propagation of the light is the Diffuse Optical Tomography (DOT). Near infra-red light is used to probe the medium with the aim to recover the spatial distribution of the optical parameters, such as scattering and absorption. Light travelling between any points on the surface spreads out over the tissue and therefore reaches almost all remaining sensors.

In our arrangement it is assumed that light travels in straight lines between optical sensors through the transparent medium (ambient fluid), and unlike in DOT is not scattered at all. Although the reconstruction process is simplified comparing to DOT, one still has to use an imaging equipment which measures the intensity of light on optical sensors. For the purpose of this work it is required to simulate the process of light propagation (see Fig. 2). We can simply calculate the visibility of the sensors, close this information into a matrix and then extract data concerning the location of the area of reconstruction.

The visibility matrix is based on analysis of the behavior of light traveling through a homogeneous and transparent medium. It defines the visibility between nodes of investigated domain. This matrix is a result of detection process whether along line segment connecting two nodes there are or not hiding them elements. As elements we understand here a set of line segments that create two boundary layers in 2D space (see Fig. 2).

The basic idea of the visibility matrix algorithm consists of following steps. For each node of the outer layer we find connections to remaining nodes. Connection is defined by a line segment described by parametric equation. We make all possible combinations of these connections determining whether or not a given line segment has an intersection with one from the set of line segments of internal layer. Then, we successively fill in the visibility matrix putting ones for pairs of nodes that see each other and zeros for those separated by any elements. As a result we obtain matrix depicted in Fig. 2.

We choose quite naive algorithms that examine each pair of segments, but it is completely justified by the relatively low complexity of the problem (low number of line segments in the whole domain).

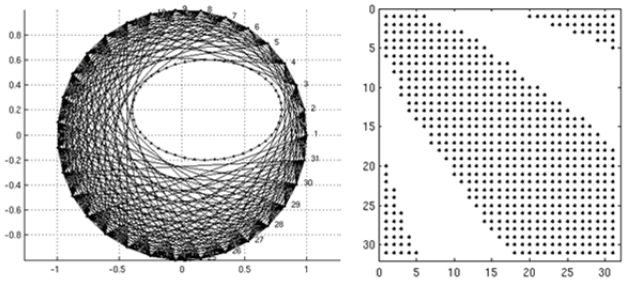

Fig. 2. The visualization (on the left) of the process of creating the visibility matrix (right)

Having the visibility matrix, a shape of the internal object can be found. The visual hull algorithm is known solution of shape reconstruction on the basis of set of shadow images (silhouettes) [4]. Since in our system images are with very low resolution (small number of optical sensors), the approach can be treated as a point-to-point visual hull problem [5].

Even though problem defined above is rather simple challenge for computational geometry, the literature query doesn't show a long list of previous solutions [6]. We decided to develop simple iterative algorithm based on the cutting lines. Starting from initial external shape, cutting is done for every ray defined by element of visibility matrix which are adjacent to the 'empty' element. Since visibility matrix is symmetric only half of it has to be inspected. Finally we get polygon which is surrounding real object inside.

The polygon obtained by the optical reconstruction is meshed, to define inverse EIT problem (as seen in Fig. 3).

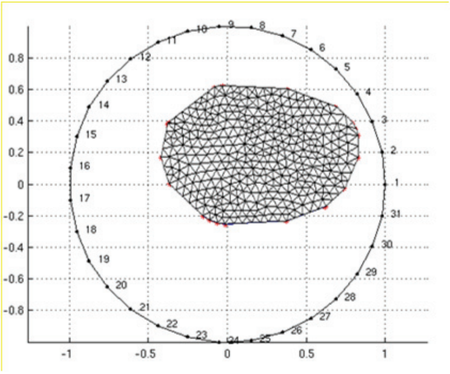

Fig. 3. External shape of the object determined by the use of visibility methods

This part of work definitely needs further investigation. One can realize that proposed solution always produce larger objects than they really are, for biological problems some smoothing seems to be appropriate, numerical efficiency could be also improved.

Inverse EIT reconstruction

The standard reconstruction problem is often formulated as a non-linear least squares optimization, where the object function is the distance between the measured data and the data obtained in a forward simulation with an estimate of the conductivity distribution.

$$\sigma = \min \| V_m - V(\sigma) \|^2 \qquad (1)$$

The Gauss-Newton iterative scheme is well know algorithm for this kind of problems:

$$\sigma_{i+1} = \sigma_i + \Delta\sigma \qquad (2)$$

where the conductivity image update step in each iterations is expressed as:

$$\Delta\sigma = J^{-1}(V_m - V(\sigma)) \qquad (3)$$

Usually the number of unknowns is different than the number of measurement data points, so Moore-Penrose pseudo-inversion should be applied [8]:

$$\Delta\sigma = (J^T J)^{-1} J^T (V_m - V(\sigma)) \qquad (4)$$

As always, the EIT problems are ill-posed, so some form of a regularization is advised. In this paper we use simple Tikhonov regularization, which introduces an additional term to the equation (4):

$$\Delta\sigma = (J^T J + \alpha^2 I)^{-1} J^T (V_m - V(\sigma)) \qquad (5)$$

To solve eqn. (5) we need $V(\sigma)$ and J, with the value of the hyper-parameter α chosen experimentally.
$V(\sigma)$ is a classic solution of the forward problem; in this case solved by Finite Element Method (EIDORS package [7]). Jacobian matrix J is calculated using an adjoint field method, as defined in [9].

One of the most important aspects of a successful reconstruction algorithm is the utilization of as much of a priori knowledge as possible [3]. Accordingly, in constructing the solution we utilize the following information: the shape of the object, its location with respect to the electrodes, the properties of the ambient liquid, and the precise location of the electrodes. Our method is based on the idea called dual meshing. Fine mesh is used to determine Jacobian in the forward problem and a coarse mesh is for the inverse problem. The forward problem is well posed, so the high mesh density allows for a high accuracy of the computations. In contrast, the inverse problem is ill posed; hence, it is beneficial to lower the number of unknowns. Furthermore, the use of different meshes for forward and backward problems allows for automatic avoidance of typical reconstruction pitfall called 'the inverse crime' [3].

Dual meshing is based on the a projection matrix P, which defines the relation between the two meshes: P converts the coarse conductivity mesh into the fine one:

$$\sigma_f = \mathrm{P}\sigma_{\mathrm{c}} \qquad (6)$$

The method is actually difference reconstruction. It means that the difference between the known background image and the proper solution (marked as σ_{cd}) is used as an unknown. Since the background image σ_0 is based on the forward mesh, the real solution is given by following formula:

$$\sigma_f = \sigma_0 + \mathrm{P}\sigma_{\mathrm{cd}} \tag{7}$$

Demonstration

Preliminary validation of the method is based on simple 2D model, where elliptical shape object was immersed into the circular electrode tank. As seen in Fig. 4a) homogeneous structure of the object was disturbed by small inclusion with conductivity higher by 10% than surrounding tissue. This case could be understood as tomography of a simplified model of the breast with tumor.

Mesh of complete model, Fig. 4a), has fairly fine discretization, what ensure high quality of the forward simulation. The fine mesh consists of 9608 elements. Forward problem is well posed, so such size doesn't introduce computational challenge for modern computers.

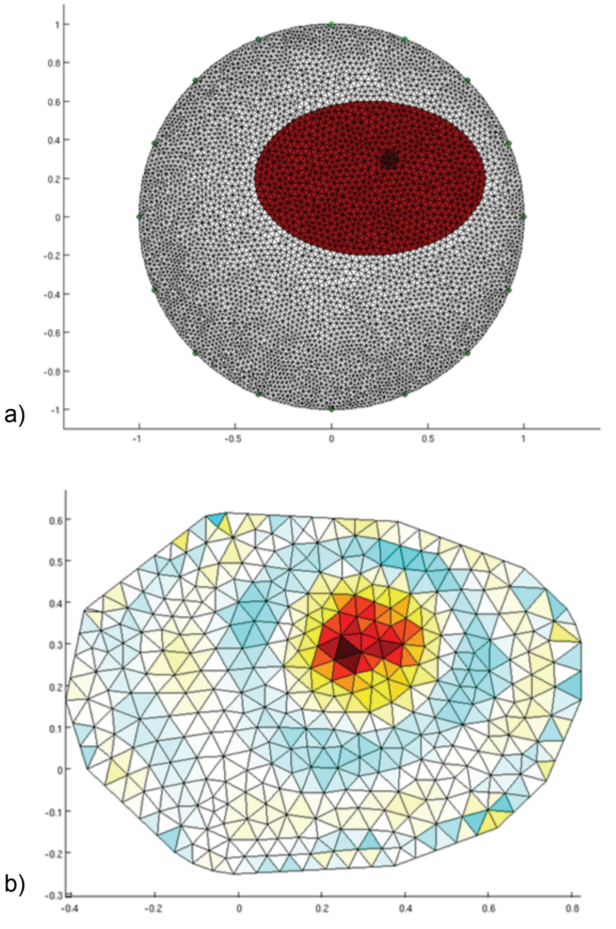

Fig. 4 Validation on 2D object with single inclusion. a) Model used to simulate measurements (9608 elements), b) Reconstructed image of the object (677 elements)

The first stage of the solution is deployment of optical shape reconstruction to determine location and shape of the object floating in the electrode tank. It was already discussed in the previous subsection and presented in Fig. 2 and 3. This way we obtain coarse mesh for inverse problem, which has only 677 elements. Such small size of the problem benefits by extraordinary speedup of inverse calculation. Typically solution is ready after only few seconds. That wouldn't be the case if one used the fine mesh for inverse problem.

As seen in Fig. 4b) internal structure of the object was reconstructed fairly correctly. It is visible that inside the breast model there is single tumor inclusion. Location and the size are also roughly proper. Of course those are preliminary results, and quality of reconstruction should be the subject of further works, but one to be aware that EIT images are always lower quality comparing to other imaging modalities, such as CT or MRI.

Conclusions

The aim of this paper was to present method to eliminate problems related with electrodes during EIT imaging. Described solution is based on the extra layer of fluid in which investigated object is floating. Essential part of the algorithm is determination of shape and location of the object. One could solve such problem by standalone impedance method, but our method incorporates two different reconstruction techniques, taking into account different properties of the object. Optical shape reconstruction use transparency information, while impedance tomography is based on the conductivity distribution. Those parameters are independent, so it could be proved that result is higher quality comparing to the single modality imaging.

Main advantages of EIT, such as safety, short imaging time, low cost are still valid for presented setup, while electrode problems are eliminated completely. The approach has to be considered as a preliminary proof of the concept. A lot of research work has to be done before this new concept could be verified experimentally, but authors are convinced that such afford is worth to be taken.

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***Authors**: dr inż. Bartosz Sawicki, dr inż. Tomasz Grzywacz, Politechnika Warszawska, Instytut Elektrotechniki Teoretycznej i Systemów Informacyjno-Pomiarowych, ul. Koszykowa 75, 00-662 Warszawa, e-mail: sawickib@iem.pw.edu.pl.*