Moisture analysis of building walls using tomographic measurements

Abstract. The article presents the analysis of building walls humidity by means of tomographic measurements. The use of modern tomographic techniques allows for spatial assessment of humidity levels. The proposed application solves the inverse problem in electrical tomography. The measuring system contains special electrodes for measuring humidity. The application includes a number of different methods of image reconstruction, such as the level set methods, LARS, or elastic net.

Keywords: electrical tomography, sensors, inverse problem.

Introduction
The article presents the reconstruction of the image obtained using the NX EIT wall system prototype [1]. The application is designed to analyze the humidity of the walls. It includes many methods to solve the inverse problem in electrical impedance tomography (EIT). In the considered case, methods of problem optimization are used [2-15]: To solve the inverse problem, several methods based on deterministic, topological and machine learning methods were implemented. [16-46].

Methods
The subject of the analysis in this study are image reconstructions of a selected data frame obtained using a program created in MATLAB. The said application is used to analyze the humidity of the walls. It includes a number of different methods to solve the inverse problem in electrical impedance tomography (EIT).

Electric field potential (satisfies the generalized Laplace equation, which in the Cartesian coordinate system is clearly written as:

$$\frac{\partial}{\partial x}\left(\sigma \frac{\partial \phi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\sigma \frac{\partial \phi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\sigma \frac{\partial \phi}{\partial z}\right) = 0$$

The above equation is solved with appropriate boundary conditions. In the case under consideration, the following methods were used to optimize the objective function:

- Gauss-Newton method with Tikhonov regularization (GN-T)
- Gauss-Newton method with Laplace regularization (GN-L)
- regularization based on total function variation (TV)
- contour level method (LSM + GT + FEM)
- Elastic Net regularization (EN)
- artificial neural networks (ANNs)

Electrical voltages measured between specific electrode pairs are shown in Figures 1 to 6. The following markings were used:

- U - data frame (measuring voltages)
- U(\sigma_{rec}) - voltages calculated on the basis of specific conductivity \(\sigma_{rec}\)

The quality of the reconstruction is determined by the percentage error:

$$PE = \frac{\| U(\sigma_{rec}) - U \|_2}{\| U \|_2} \cdot 100\%$$

The correlation coefficient between the voltages \(U\) and \(U_{(\sigma_{rec})}\) was calculated based on the formula:

$$PE = \frac{\| U - U_{(\sigma_{rec})} \|_2}{\| U \|_2} \cdot 100\%$$

Results
The list of finite element mesh parameters for numerical calculations is presented in Table 1. The results of image reconstruction and distribution of electrical voltages are shown in Fig. 1-8. Tables 2 and 3 show the parameters and quality of the reconstruction.

Table 1. List of finite element mesh parameters.

<table>
<thead>
<tr>
<th>Spatial dimensions</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of electrodes</td>
<td>16</td>
</tr>
<tr>
<td>Electrode Type</td>
<td>point</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>1588</td>
</tr>
<tr>
<td>Number of finite elements</td>
<td>2908</td>
</tr>
</tbody>
</table>

Table 2. List of reconstruction parameters for deterministic methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Regularization parameter</th>
<th>The number of iterations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN-T</td>
<td>1.0E-2</td>
<td>20</td>
</tr>
<tr>
<td>GN-L</td>
<td>1.0E-2</td>
<td>20</td>
</tr>
<tr>
<td>TV</td>
<td>1.0E-2</td>
<td>15</td>
</tr>
<tr>
<td>LSM+GT+FEM</td>
<td>not applicable</td>
<td>250</td>
</tr>
</tbody>
</table>

Fig. 1. Electrical voltages - GN-T method.
Fig. 2. Electrical voltages - GN-L method.

Fig. 3. Electrical voltages - TV method.

Fig. 4. Electrical voltages - LSM.

Fig. 5. Electrical voltages - EN.

Fig. 6. Electrical voltages - ANNs.

Fig. 7. Image reconstructions obtained using the methods: GN-T (a), GN-L (b) and TV (c). The area marked with navy blue is characterized by increased conductivity (high humidity).

Fig. 8. Image reconstructions obtained using the LSM + GT + FEM (a), EN (b) and ANNs (c) methods. The area marked with navy blue is characterized by increased conductivity (high humidity).
Table 3. Parameters determining the quality of the reconstruction.

<table>
<thead>
<tr>
<th></th>
<th>GN-T</th>
<th>GN-L</th>
<th>TV</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>12.3452%</td>
<td>10.8514%</td>
<td>0.1469%</td>
</tr>
<tr>
<td>PCC</td>
<td>0.9524</td>
<td>0.9303</td>
<td>1.0000</td>
</tr>
<tr>
<td>LSM + GT + FEM</td>
<td>EN</td>
<td>ANNs</td>
<td></td>
</tr>
<tr>
<td>PE</td>
<td>0.5119%</td>
<td>36.0784%</td>
<td>14.0470%</td>
</tr>
<tr>
<td>PCC</td>
<td>1.0000</td>
<td>0.9330</td>
<td>0.9912</td>
</tr>
</tbody>
</table>

Conclusion

The article presents a system for assessing the humidity level of buildings using electric tomography. The use of modern tomographic techniques allowed for spatial assessment of humidity levels. The proposed application solves the opposite problem. The measuring system contains special surface electrodes. The solution includes a number of different methods for image reconstruction, such as level set method, total variation, neural networks, or elastic net.

The optimization methods used allow for correct image reconstruction determination. Thus, it is possible to precisely indicate the location of an area with increased humidity. The best results (the lowest percentage error and the largest correlation coefficient) were obtained in the case of the TV and FEM + GT + FEM methods. The reconstruction obtained using the statistical method (EN) is subject to a relatively large percentage error. It is related to the specificity of the data set, on the basis of which the coefficients of the linear model were determined. It should be noted that the relationship between electrical voltage and conductivity is non-linear. In addition, in the considered case, the ratio of wet conductivity to dry conductivity is quite large and is 10 - the linear approximation may not function satisfactorily.

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