Planar Array 3D Electrical Capacitive Tomography

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Abstract—Electrical capacitance tomography (ECT) is a promising non-invasive imaging technique that is capable of imaging the dielectric permittivity properties of an object. There are a number of potential applications for ECT where there is only limited access to the targeted objects, making conventional circular array impractical. In this paper, a planar array ECT system is developed and proposed for 3D sub-surface imaging as a form of limited access tomography. The sensor development, practical implication, capability and limitation of the proposed planar array ECT are discussed. The experimental results are used to evaluate the system performance. A depth of up to 53\% of the length of sensor array can be achieved using experimental data using an array of 3 x 4 electrodes.

Keywords: 3D electrical capacitance tomography, planar array electrical capacitance tomography, subsurface tomography

1 Introduction

Electrical Capacitance tomography (ECT) is a type of imaging technique which has been developed in industrial process tomography applications since the late 1980s and early 1990s [1]. ECT is capable of generating permittivity maps inside an object by measuring the inter-electrode capacitances for all combinations of electrodes usually surrounding the object. This is achieved by systematically applying a potential to an excited electrode and measuring the inter-electrode capacitance between the excited electrode and every other electrodes, whilst ensuring all other electrodes are kept at ground [1,10]. From the capacitances measurements, an image is then constructed by calculating the distribution of the changes in permittivity [5]. To date, most ECT systems, which have been developed, have been designed and built using a traditional arrangement of electrodes, where the electrodes are arranged circumferentially around the target object [3, 5,6]. This type of arrangement has a circular or rectangular geometry and requires free access around the complete periphery, where 'full access tomography' can be achieved [1, 5, 7, 8, 10]. However, there are number of potential applications where it may be difficult to detect or examine the object in a 360 degree case and image reconstruction cannot be implemented using a traditional ECT system. In order to overcome this limitation a novel ECT system is currently being designed with a planar ECT sensor as a form of 'limited access tomography' which is able to realise 3D visualization for near and sub-surface imaging. The method proposed here can be used in other types of electromagnetic imaging methods [15-22].

There has been growing interest in planar array ECT for several new application areas in past few years. In [24] a single image of a 3D planar ECT was shown for flow imaging but no analysis was given. In [25] commercial finite element software was used to model the forward problem for 3D planar array ECT. In [26] a 2D imaging of planar array ECT was presented for a possible security scanning application. In [26] the authors have mentioned the relevance and importance of possibility of 3D subsurface imaging using planar sensor and that is the subject of this study. A single sided capacitive imaging system was developed in
[27] for non-destructive testing (NDT) applications. The system was applied to several NDT applications such as inspection of composite materials [28]. The capacitive imaging system is using an array of 2 or 4 electrodes. In [28] the authors stated the advantages of an array imaging for rapid inspection. The array ECT imaging presented in this paper will provide higher inspection speed with a 12 electrodes array as well as improved depth detection with the additional measurements between non-adjacent electrodes.

In this paper the development of planar sensor model and system setup is presented, followed by experimental evaluation. Series of experiments were carried out and demonstrated in this paper, near surface imaging in 3D.

2 Sensor description

The planar sensor array that was built consists of 12 electrodes which were constructed using conductive copper tape as shown in figure 1 below. The 12 electrodes were arranged in a 4 x 3 matrix array and attached to a plastic square plate with an area surface of 25cm x 25cm and 4mm in thickness; the length of electrode array is 17 cm x 17 cm, between electrodes and surrounding area of the sensor array includes grounded conductors. A thin conductive ground of 5 mm is used to separate electrodes. The planar electrodes are attached to a 2 mm thick plastic plate with relative permittivity of 1.6. On the back side of the sensor array a metallic shield used to partly shield the planar array from external interferences. The measurement of capacitance data were carried out by using from process tomography limited, PTL, (http://www.tomography.com/), PTL 300E ECT system where 12 channel capacitance measurements are possible using a pulsed excitation with frequency of 1.25 MHz based system which allows capacitance values down to 0.0003pF (0.3 femtoFarads) to be resolved. This ECT system is capable of data collection in 100 frame/second making it suitable as a rapid imaging device.

![ECT 3D measurement system and electrode arrangements in the array.](image_url)
3 Image reconstruction

To solve the ECT image reconstruction problem the forward simulations are required. In the ECT, the forward problem is the simulation process of calculating the electric potential distribution and capacitances based on the geometric information of the electrical sensor, and excitation and measurement pattern.

In a typical ECT real measurement process, the excited electrode is subjected to a sinusoidal voltage while all other electrodes are ground; the total potential is measured on each of the remaining electrodes. All electrodes act as excited electrode in turn similar to the classic circular arrangement. For this reason, the number of measurements has relationship with the number of electrodes given by, \( M = \frac{N(N-1)}{2} \), Where M is the number of independent measurements and N is the number of electrodes.

There are several significant assumptions in the analysis that should be pointed out, namely that it is assumed there are negligible internal charges and wave propagation effects and that the electrostatic approximation \( \nabla \times E = 0 \) , for an electric potential \( u \), and \( E = -\nabla u \) . According to Poisson’s equation the mathematical model for an ECT forward problem can be formulated as,

\[
\nabla \cdot (\varepsilon \nabla u) = 0 \quad \text{On } \Omega
\]

where \( \varepsilon \) is the dielectric permittivity, \( u \) is the potential, and \( \Omega \) indicates the region including electrodes, shielding and the imaging region. The electric potential is fixed on each electrode and the boundary conditions can be defined as \( u = v_k \) on \( \Omega \), where \( v_k \) is the voltage signal which is applied on the excited electrode and is zero on all other sensing electrodes. Capacitance of electrode \( k \) can be expressed as below,

\[
C = \frac{Q_k}{v_k} = \frac{1}{v_k} \int_{\Omega} \varepsilon \frac{\partial u}{\partial n} d\Omega
\]

where \( n \) is the inward normal on the electrode number \( k \). The finite element method can be used to satisfactorily solve this problem. By using Galerkin’s approximation [1], the boundary value problem reduces to a linear system of equations,

\[
A(\varepsilon)U = B
\]

Where \( A \) is system matrix for the discrete representation of \( \nabla \cdot \varepsilon \nabla \) and \( B \) is the boundary condition term and \( U \) is the vector of electric potential solution. In experimental ECT systems, the capacitance data is normalized by using a process of calibration. The normalized capacitance is (for each capacitance measurement \( Q_k / v_k \)),

\[
\lambda = \frac{C_{\text{meas}} - C_{\text{air}}}{C_{\text{high}} - C_{\text{air}}}
\]

where \( C_{\text{air}} \) is the capacitance measurement for free space, \( C_{\text{meas}} \) is the simulated or experimental capacitance data capacitance measurement and \( C_{\text{high}} \) is the capacitance measurement when the imaging region is filled with high permittivity objects. In case of
planar ECT, a wooden block covering region of interest for imaging was used for $C_{\text{high}}$. The wood block has a size of 17 cm x 17 cm x17 cm which covers area of interest for imaging over the surface of planar array ECT. Figure 2 shows the meshed model generated by Netgen [11] with the same geometry as the experimental planar sensor (Table 1), number of elements in this mesh is 81834. By solving the forward model [3] it is possible to evaluate the capacitance data, which then can be used in inverse problem.

![Figure 2: Mesh model for the planar sensor](image)

Proposed sensor has 12 electrodes hence there are 66 measurements, as shown in figure 3 which shows the capacitance data for both simulated and experimental case for free space. A complete sensor model can further improve the accuracy of the forward model [8], but also make the computational of the forward model more costly.

![Figure 3: Simulated and measured capacitance, to get the absolute value of the capacitance, the relative capacitance should be multiplied by the free space permittivity.](image)

The relationship between measured data capacitance and the permittivity of each voxel is non-linear; therefore a Jacobian matrix is used to linearize this relationship. Each row of the Jacobian matrix represents the sensitivity of one measurement data with respect to all voxels. Each row of the Jacobian matrix (also called the sensitivity map) indicate the relationship between capacitance and the permittivity of each combinations of electrodes [1,7].

The capacitance measurements between different combinations of pairs of electrodes can be defined as a nonlinear function of the permittivity distribution. Hence $C=F(\varepsilon)$, where $C=[C_{1,2}(\varepsilon), \ldots, C_{1,N}(\varepsilon), C_{2,3}(\varepsilon), \ldots, C_{N-1,N}(\varepsilon)]^T$ and is the capacitance vector consisting of all...
capacitance measured of all possible combinations of two electrodes, N is the number of electrodes and $F(\varepsilon)=[f_1(\varepsilon)\ldots f_n(\varepsilon)\ldots f_M(\varepsilon)\ldots]^T$. Here, M is the number of measurements. Here $\varepsilon=[\varepsilon_1,\ldots,\varepsilon_k,\ldots,\varepsilon_K]^T$ is the vector of permittivity distribution. Therefore, the change in capacitance, $\Delta C$, in response to a perturbation of the permittivity distribution, $\Delta \varepsilon$, according to equation 2, the Jacobian matrix can be defined as follows

$$
\Delta C = J \cdot \Delta \varepsilon + O(\Delta \varepsilon^2)
$$

where $J$ is the Jacobian matrix of capacitance with respect to permittivity, which is also known as the sensitivity matrix.

Within the Jacobian matrix the derivatives indicate the change of the $m^{th}$ capacitance due to the change in permittivity at the $k^{th}$ voxels. Therefore each column of the Jacobian matrix indicates the relationship of the capacitance and the permittivity between specific two electrodes, which is the sensitivity map. An example of the sensitivity maps are shown in figure 4. While the nearby electrodes are producing higher capacitance data as shown in figure 3, the electrodes further away show good depth detection but they are noisier data.

Figure 4: Left: Sensitivity maps for electrode 1 and 11. Right: Sensitivity maps for electrode 1 and 3

Landweber based method is a commonly used algorithm to solve the inverse problem in ECT [2,13]. As stated, the main task of image reconstruction for electrical capacitance tomography is to determine the permittivity distribution from the measured capacitance. In the discrete form, it is necessary to find the unknown $\Delta \varepsilon$ from the known $\Delta C$, while $J$ acts as a constant coefficients matrix in linear image reconstruction cases. In this study an iterative reconstruction method called Landweber iteration was used [13]

$$
\Delta \varepsilon_{n+1} = \Delta \varepsilon_n + \tau J^T \Delta C - J^T \Delta \varepsilon_n
$$

where $\tau$ is the relaxation factor chosen to be 0.5 with 200 iterations for all experiments.
3.1 Image Quality Measures

Several image quality measures were presented in [12]; such as resolution (RES), positioning error (PE) and ringing effect (RNG). In this paper, a modified image quality parameter; normalized resolution (NRES) is used to define the variation of the image quality with the depth. Image resolution which is calculated using the equations defined in [12], measures the ratio of voxels number in inclusions (in the case of the experiments in this paper the wooden sample) to the total voxel number, [12]. The total voxel numbers represents the volume of region of interest for imaging. It can be defined as

\[ \text{RES} = \frac{1}{V} \sum_k \left[ \hat{x}_k \geq \frac{1}{4} \max_j \left( \hat{x}_j \right) \right] \]  \hspace{1cm} (7)

where \( \hat{x}_k \) is each voxel in the reconstruction inclusion, and \( V \) is the volume in the pixel of the true permittivity distribution. The volume ratio (VR) is the ratio of volume of target to the volume of sensor region.

\[ \text{VR} = \frac{V_{\text{target}}}{V_{\text{sensor}}} \]

Hence the normalized resolution can be calculated as

\[ \text{NRES} = \frac{\text{RES}}{\text{VR}} \]

NRES value represents relative image degradation by depth.

4 Results and discussion

Here the experimental results are presented for planar array 3D ECT system. For this study extensive simulation studies have been carried out, which shows the feasibility of 3D planar array ECT imaging. In this paper we extended the simulation study to systematic experimental tests. Wooden samples with relative permittivity of approximately 2 are used for these experiments. Single object and multiple object reconstruction as well as depth evaluation results are presented here.

4.1 Single object testing

In this experiment, single objects in different size, were placed very close to the sensor at different locations on the planar array as shown in the left hand column in figure 5 and figure 6. Two dry wooden blocks were tested as a target sample. The larger wood block (sample A) was 150mm x 50mm x 50mm and is shown figure 5, while the smaller block was 50mm x 50mm x 50mm (figure 6). Examination of figures 5 and 6 shows that the planar ECT system is able to reconstruct single objects in any location when it is very near to the sensor region for both samples tested. In order to carry out testing the performance on multiple objects, the experiment was carried out as shown in the following section.
Figure 5: Results of reconstruction of single object in different location near the sensor (150 x 50 x 50mm target). Left: true object, middle: cross sectional image, and right: isosurface image.
Figure 6: Results of reconstruction of single object in different location near the sensor (50 x 50 x 50mm target).

Left: true object, middle: cross sectional image, and right: isosurface image

4.2 Multiple object testing

In this section, the experiment of detecting multiple objects using the planar ECT sensor has been demonstrated. A variety of wooded blocks (50mm x 50mm x 50mm) were tested in different locations near the sensor surface as shown in figure 7.
Figure 7: Results of reconstruction of multiple objects in different location near the sensor. Left: true object, middle: cross sectional image, and right: isosurface image

Figure 7 shows that the actual sensitivity of the planar ECT sensor is capable of detecting multiple objects attached to the sensor; for example when the wooden blocks were fairly close to each other it was still possible to discriminate between the two blocks.

4.3 Depth detection
In previous two sections, the feasibility of the planar ECT system was investigated for object(s) close to the plan array sensor. In this section, the depth of penetration of the planar ECT system for potential sub-surface imaging application will be examined. As shown in figure 8, the test involved hanging an object from a steel rig which is far enough from the sensor so as to minimize its influence to the system. The object was placed between the 6th and 7th electrode while the distance between the object and the sensor was varied in steps of 1cm in order to determine the maximum depth the planar ECT sensor.

Figure 8: Experimental set-up for depth sensitivity

<table>
<thead>
<tr>
<th>Distance</th>
<th>Slice image</th>
<th>3D View</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 cm</td>
<td><img src="image" alt="Slice Image" /></td>
<td><img src="image" alt="3D View" /></td>
</tr>
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As shown in figure 9, there is a drop in the sensitivity of the planar ECT sensor that consequently results in decrease of resolution of the reconstructed results as the distance between the test object and sensor increased. The maximum distance the system was still able to noticeably detect the wooden object was at least 6 cm for an array of 17 cm x 17 cm (area of electrode array), this shows a detectability of better than 53% of depth detection. Resolution plot against the depth is shown in figure 10.

Figure 10 above shows that the change of resolution of the reconstructed image with varying depth of the object moving away from the sensor. With respect to the first three tests, the
resolution remains above 90% and goes down slightly when the depth is less than 3 cm. The resolution drops sharply when the depth reaches 4 cm and is totally lost after the depth goes above 9 cm.

5 Conclusions

The capability and feasibility of a planar ECT system has been demonstrated in 3D. This type of electrode geometry makes imaging of the near sub-surface possible. The approach is a very challenging imaging setup since the access to the targeted object is limited to one surface only. Furthermore, it is verified that planar ECT is capable of detecting the object in the sub-surface. The experimental results show that although the in-depth detection using planar ECT is limited up to 65% of length of sensor array, but the accuracy goes down as the sample is getting further. Objects located in central area of sensor array are better detected than the objects at the edge of electrode array. This is due to the fact the object in centre is closer to more neighbouring electrodes combinations, which has a better quality in measured signals. The planar ECT has potential to be used as a sub-surface imaging tool in application where a circular ECT electrode array is inappropriate. Future work will look at improving the detectability of the system, increasing the resolution and depth detection and examine the feasibility of planar ECT in a variety of possible applications such as landmine detection and material inspection.

References:


