4D Scanning for Planar Array ECT

C. T. Chittenden*, M. Soleimani

Electrical Tomography Lab, University of Bath, Bath, UK

*Email: C.Tholin-Chittenden@bath.ac.uk

ABSTRACT

Temporal tomography imaging involves taking multiple images of the same area and tracking changes. This has been done with good results using Electrical Impedance Tomography (EIT) (Adler, Dai and Lionheart, 2007) as well as Electrical Capacitance Tomography (ECT) (Soleimani *et al.*, 2009). However both of these focus the sensor on a single area and measure over time but in a landmine detection scenario, and other applications, it is the sensor which must move over an area. This allows for not only 4D reconstruction using multiple 'frames' of measurement data but also to build up a much larger imaging area than the size of the sensor.

This paper proposes a method which uses temporal image reconstruction whilst also moving the sensor over an area to reconstruct a more accurate and stable permittivity distribution. There is overlap of viewing regions between each movement of the sensor and so the reconstruction Jacobian and capacitance measurements are concatenated to then produce much larger reconstructions. This is referred to as 'scanning' with the aim to build up an image of the entire 'scanning' area. This method is better than stitching together individual images next to each other as each voxel of the image is reconstructed from multiple measurements. Initial simulation work has shown that this works much better than non-scanning where only a snapshot of the viewing area is reconstructed. Practical testing also showed that this works with real data and both shape and location reconstruction of the inclusion are improved.

Keywords 4D ECT Landmine Scanning

Industrial Application General

1 INTRODUCTION

4D tomography is where temporal image reconstruction is used to improve the image reconstruction by using multiple 'frames' of measurements. This is useful when spatial resolution is very low but temporal resolution can be much higher.

Electrical Impedance Tomography (EIT) has excellent temporal resolution and this has been used to improve spatial resolution when imaging a fast changing situation such as that of the human body (Adler, Dai and Lionheart, 2007).

However unlike landmine detection this application is imaging a changing region with a static sensor, as opposed to the other way round. The difference for landmine detection is that the inclusion is static in the ground and the sensor moves over the surface. This means that not only can an image under the sensor be reconstructed from multiple sensor positions over a small area, but also a large area image can be reconstructed using a small sensor if it is moved sufficiently.

4D tomography has also been implemented with Electrical Capacitance Tomography (ECT) (Soleimani *et al.*, 2009) but again as with the EIT temporal imaging it uses a static sensor to measure a changing region, in this case flow in a pipe. In a different format of ECT, circular fringing-field sensors were used in a planar array to scan objects and produce good images and even detect material type (Frounchi and Dehkhoda, 2003). However this method was limited to objects at a distance of ≈ 3mm from the sensor as each element of the planar array was an individual sensor. But the method of moving the sensor across the imaging region slowly and combining the results to produce 1 image is the same as the requirement in landmine detection.

ECT is much more feasible for landmine detection as it is a non-invasive method which won't risk detonating the mines. EIT has been used for landmine detection (Church *et al.*, 2001) but it involves inserting metal rods into the ground as it requires direct contact with the ground. ECT does not and the sensor would be able to stay safely above the ground surface with no contact.

2 THEORY

2.1 Electrical Capacitance Tomography (ECT)

ECT imaging relies on how an electric field through an area will be affected by the atoms in this area. When an electric field is applied through an atom, the electrons and nucleus which are oppositely charged will shift slightly due to the forces pulling them in different directions. This shift polarises the atom and the same thing happens to every atom which the electric field passes through. This shifts the overall charge across the entire area.

In ECT the electric field is applied across the area used 2 electrodes which essentially form a capacitor with the viewing region between them. The atoms in this region polarise, and the overall charge shifts which affects the charge built up on each electrode. The charge difference between the electrodes is capacitance and this can be measured by a measurement device. Different types of atoms shift, or polarise, differently and therefore affect the capacitance differently. Measuring the capacitance can indicate what types of atoms are in between the electrodes. The polarisation of the atoms is dictated by a property called permittivity and the larger the permittivity of an atom, the more it polarises and the more it affects the capacitance.

A permittivity image can be built up by using an array of electrodes and measuring capacitance between each unique combination of the electrodes. How this is done can be broken down into 2 parts. The forward problem and the inverse problem.

The forward problem focuses on simulating a theoretical model of the electrode array and the viewing area to find out how each individual electrode pair capacitance will be affected by different permittivity values across the viewing area. Using Gauss's electricity law an equation to calculate electric potential, and therefore electric field, through the region can be derived (Tholin-Chittenden and Soleimani, 2017):

$$\nabla \cdot (-\varepsilon \nabla \phi) = 0 \tag{1}$$

where ε is permittivity and ϕ is electric potential. Charge is the surface integral of electric flux through an area which means that capacitance can be defined as:

$$C = \frac{1}{V} \oint_{\Omega} \varepsilon \nabla \phi \, d\omega \tag{2}$$

where V is the excitation voltage, Ω is the surface area made up of elements ω. This shows that capacitance is a function of permittivity and this can be linearised through Taylor expansion to produce:

$$\Delta C = J \Delta \varepsilon \tag{3}$$

where J is the jacobian which is essentially a 'sensitivity distributions' for each electrode pair showing how each voxel of the permittivity distribution is affected by each capacitance measurement.

The second part is the inverse problem which attempts to produce a permittivity distribution from the Jacobian and the capacitance measurements. This part attempts to solve equation 3 to find ε but as J is rarely square it cannot simply be inverted. A method that can do this is Linear Back Projection (LBP) (Xie *et al.*, 1992) but it can be improved by adding some form of regularisation which is what Tikhonov Regularisation (Neubauer, 1989) does. Tikhonov Regularisation solves for ε with the following equation:

$$\Delta \varepsilon = (J^T J + \alpha^2 I^T I)^{-1} J^T \Delta C \tag{4}$$

where α is the regularisation parameter, and I is the identity matrix. This is what will be used to reconstruct all permittivity distributions and using this on its own is referred to as a ‘non-scanning’ method.

2.2 Scanning Method Theory

The scanning will be implemented by using a static inclusion where the sensor is then moved over it, and a constant area below the sensor head is reconstructed each time.
Temporal reconstructions will be created by concatenating Jacobians and Capacitance measurements at each position of the sensor head.

Position 1: $$J = J_1$$

Position 2: $$J = \begin{bmatrix} J_1 \\ J_2 \end{bmatrix} \tag{5}$$

This then results in reconstructing the same size area but using more measurements each time.

When moving the sensor across an area, the voxels below the sensor shift which each movement of the sensor relative to the sensor position. This means that the ‘sensitivity distributions’ of the Jacobian also need to be shifted so that the voxels match up.

Equation 5 shows and example of a 1x3 viewing area shifted by 1 voxel each time. When a shift occurs and a previous Jacobian value doesn’t exist it is replaced by a 0 so that this voxel is not reconstructed with that capacitance measurement.

Position 1: $$J = \begin{bmatrix} j_{1,1} & j_{1,2} & j_{1,3} \\ j_{2,1} & j_{2,2} & j_{2,3} \\ j_{3,1} & j_{3,2} & j_{3,3} \end{bmatrix} \qquad \Delta C = \begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \Delta c_3 \end{bmatrix}$$

Position 2: $$J = \begin{bmatrix} j_{1,2} & j_{1,3} & 0_{1,4} \\ j_{2,2} & j_{2,3} & 0_{2,4} \\ j_{3,2} & j_{3,2} & 0_{3,4} \\ j_{4,1} & j_{4,2} & j_{4,3} \\ j_{5,1} & j_{5,2} & j_{5,3} \\ j_{6,1} & j_{6,2} & j_{6,3} \end{bmatrix} \qquad \Delta C = \begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \Delta c_3 \\ \Delta c_4 \\ \Delta c_5 \\ \Delta c_6 \end{bmatrix} \tag{6}$$

Position 3: $$J = \begin{bmatrix} j_{1,3} & 0_{1,4} & 0_{1,5} \\ j_{2,3} & 0_{2,4} & 0_{2,5} \\ j_{3,3} & 0_{3,4} & 0_{3,5} \\ j_{4,2} & j_{4,3} & 0_{4,4} \\ j_{5,2} & j_{5,3} & 0_{5,4} \\ j_{6,2} & j_{6,3} & 0_{6,4} \\ j_{7,1} & j_{7,2} & j_{7,3} \\ j_{8,1} & j_{8,2} & j_{8,3} \\ j_{9,1} & j_{9,2} & j_{9,3} \end{bmatrix} \qquad \Delta C = \begin{bmatrix} \Delta c_1 \\ \Delta c_2 \\ \Delta c_3 \\ \Delta c_4 \\ \Delta c_5 \\ \Delta c_6 \\ \Delta c_7 \\ \Delta c_8 \\ \Delta c_9 \end{bmatrix}$$

Eventually a row might include only 0’s and therefore the corresponding capacitance measurement is no longer relevant to the current viewing area and this can be disregarded. Removing this will keep the Jacobian from getting too large and reduce number of calculations. This method has been name ‘Sparse Jacobian’ scanning as the Jacobian will be partially sparse due to missing sensitivity values.

3 EXPERIMENTAL SETUP

The scanning method will be tested both theoretically and practically. These tests will used a 12 electrode planar array ECT sensor which was developed in previous work (Tholin-Chittenden and Soleimani, 2017). The sensor head array consists of a 3x4 grid of evenly distributed electrodes which have identical surface areas. Practical capacitance measurement data will be collected by an Impedance Analyser (IA) at 100kHz excitation frequency through a custom built ECT switching board.

The reconstructions in both theoretical and practical testing will be produced with space around the sensor and also a ‘wake’ after the sensor so that with the scanning method fully reconstructed inclusions remain to be seen. This would be useful in a landmine application so that when the mine has been fully scanned, the shape and location remain in the reconstructed image.

4 THEORETICAL TESTING

In order to test the scanning theory method the DeTECT software toolbox (Tholin-Chittenden and Soleimani, 2017) was used to simulate a scanner moving past an inclusion. As the viewing region remains fixed with the position of the scanner, it appears as though the inclusion is moving, not the sensor but this is not the case.

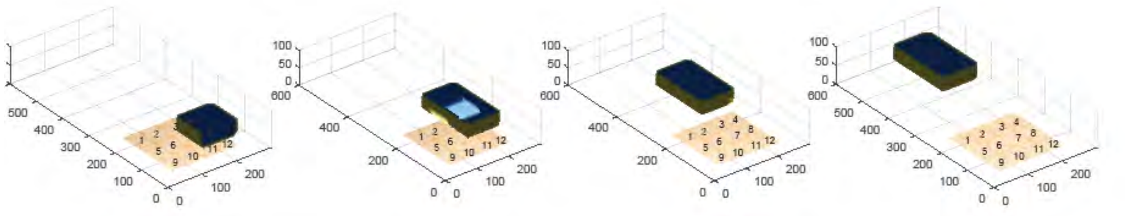

Figure 1. Simulated inclusion as sensor moves below it.

The tool box simulated theoretical capacitances that would be measured as the sensor moved below the inclusion and these were then used to reconstruct the inclusion, whilst concatenating each one and using the Sparse Jacobian scanning method. The capacitance values also had 10% noise added to them in order to more accurately recreate a real scenario.

The results in figure 2 clearly show how much better the scanning method is at reconstructing the inclusion than the non-scanning method. Even when the sensor is directly underneath the inclusion it is not able to reconstruct a good image, but the scanning method gets a better image. Toward the end the scanning method has almost fully reconstructed the inclusion.

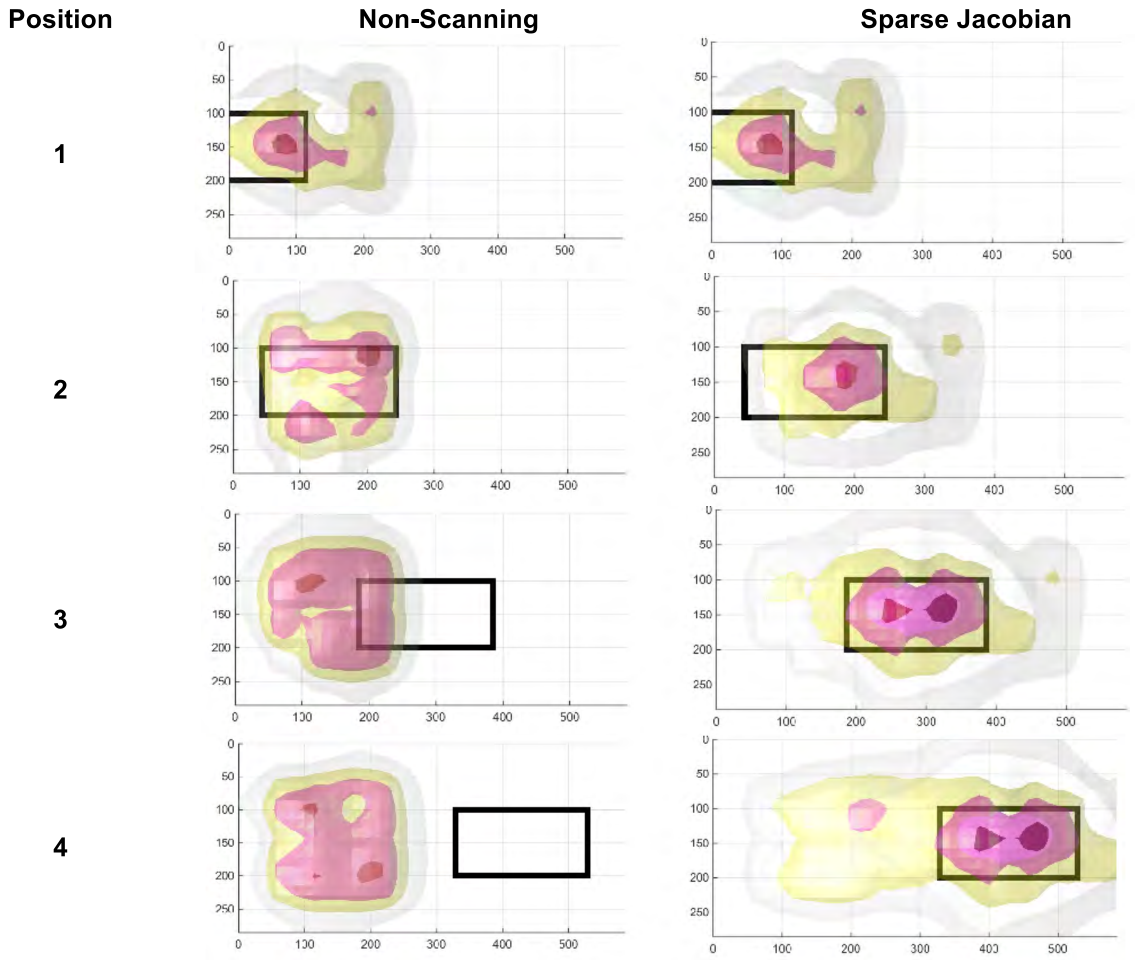

Figure 2. Reconstruction of simulated inclusion as sensor moves below it for non-scanning and scanning methods.

5 PRACTICAL TESTING

The next step is to test the method with real data to see if it is still as good as the theoretical results. This was done by leaving the sensor in a fixed position and then moving an inclusion over the top to replicate the same motion as if the sensor was moving under the inclusion. The setup of this can be seen in figure 3.

Figure 3. Experimental setup of the inclusion and sensor.

The inclusion used was a wooden cuboid which has a relative permittivity of roughly 5. This was done to keep the contrast of permittivity from the background relatively low, rather than using metal or water which have far higher permittivity values. Air has a relative permittivity of 1.

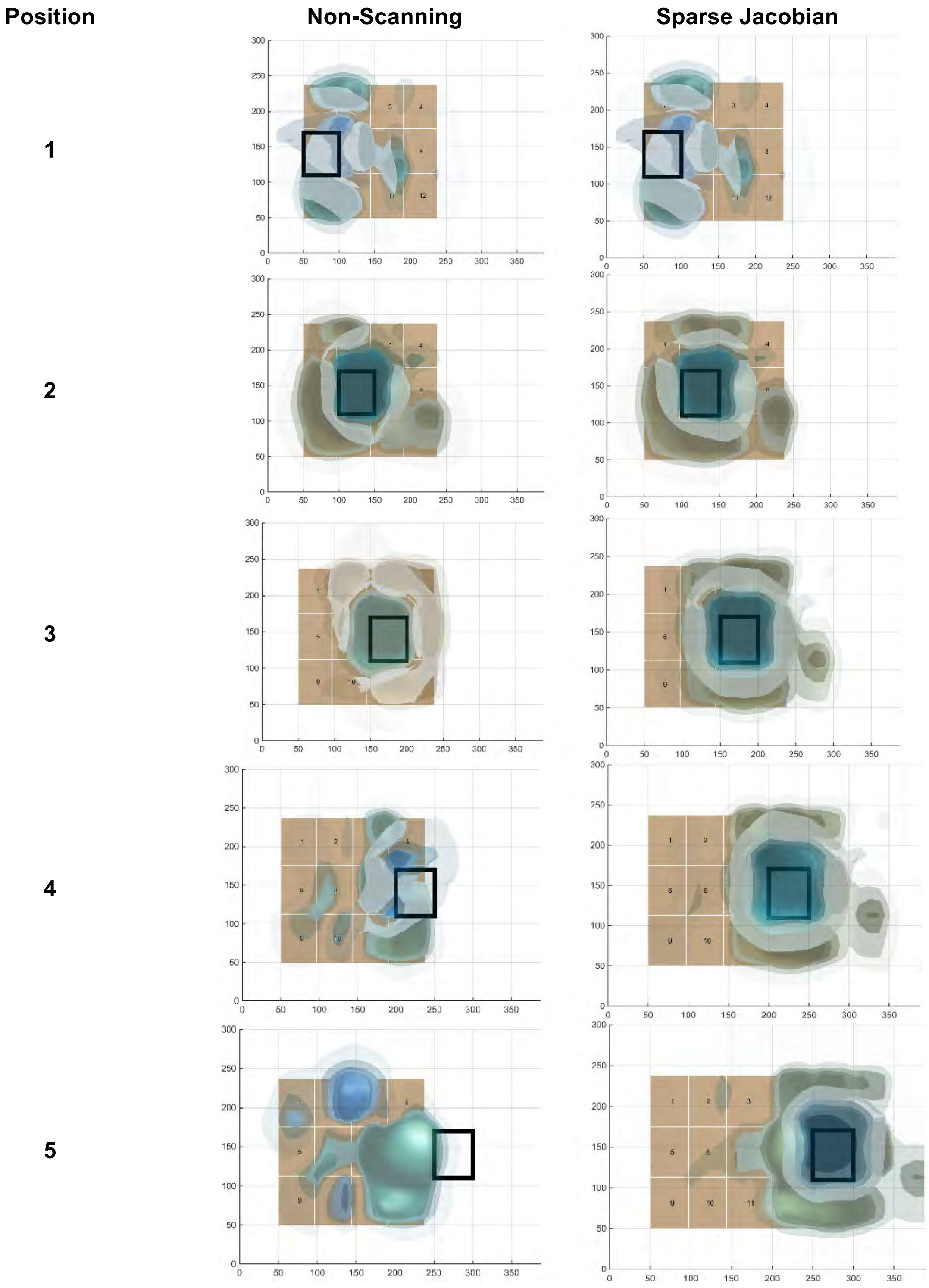

Figure 4. Reconstructions of wooden cuboid with non-scanning and scanning methods.

Figure 4 shows the reconstructions of the wooden block using real data. As with the theoretical results the scanning method is much better overall and is able to capture the location and shape of the wooden cuboid. The non-scanning method captures the inclusion well when it is directly over the centre but immediately loses it again as it moves away.

Position 3 tells a lot about how scanning improves the inclusion shape reconstruction. Commonly with planar array ECT reconstructions, the most sensitive region is the middle of the sensor and reconstructions will often reflect this. If an inclusion is left of the centre, the right side of the inclusion will be more strongly reconstructed than the other side. This can be seen in the non-scanning method at position 3. The scanning method at position 3 however is not pulled back to the centre and maintains an even shape of the reconstructed inclusion and this might be down to the use of previous measurements which captured the right hand side of the inclusion and is therefore more accurately reconstructing the shape.

6 CONCLUSION

The work in this paper has shown the feasibility and performance of using a scanning type method with a planar array ECT sensor to reconstruct better permittivity distributions. A method of 4D tomography, referred to as scanning, was developed in which Jacobians were concatenated whilst being shifted. This process was called Sparse Jacobian scanning method. It was shown to work well in a theoretical simulation despite significant noise added to the measurement signal. Also in a practical scenario the method again produced significantly better results than the non-scanning method, finding the shape and location of the inclusion well.

Further work on this method should be done to assess the computational efficiency of the method compared with non-scanning and further analyse the performance of the method. It would make sense that any scanning method required more computation as more data is used in the reconstruction but this degraded performance should be compared with benefits of the method further to conclude on the use of this method in a time critical application such as landmine detection.

REFERENCES

ADLER, A., DAI, T. and LIONHEART, W. R. B. (2007) ‘Temporal image reconstruction in electrical impedance tomography’, Physiological Measurement, 28(7), pp. S1–S11. doi: 10.1088/0967-3334/28/7/S01.

CHURCH, P. M, WORT PM, GAGNON S, McFEE J E, (2001) ‘Performance Assessment of an Electrical Impedance Tomography Detector for Mine-Like Objects’, Detection and Remediation Technologies for Mines and Minelike Targets VI, 4394. doi: 10.1117/12.445463.

FROUNCHI, J. and DEHKHODA, F. (2003) ‘High-Speed Capacitance Scanner’, in WCIPT3. Banff, Canada: ISIPT, pp. 846–852. Available at: https://www.isipt.org/world-congress/3/328.html (Accessed: 2 June 2018).

NEUBAUER, A. (1989) ‘Tikhonov regularisation for non-linear ill-posed problems: Optimal convergence rates and finite-dimensional approximation’, Inverse Problems, 5(4), pp. 541–557. doi: 10.1088/0266-5611/5/4/008.

SOLEIMANI, M, MITCHEL C N, BANASIAK R, WAJMAN R, and ADLER A (2009) ‘Four-Dimensional Electrical Capacitance Tomography Imaging using Experimental Dta’, Progress in Electromagnetic Research, 90, pp. 171–186. doi:10.2528/PIER09010202

doi: 10.1088/0967-3334/32/7/S13.

THOLIN-CHITTENDEN, C. and SOLEIMANI, M. (2017) ‘Planar Array Capacitive Imaging Sensor Design Optimization’, IEEE Sensors Journal, 17(24), pp. 8059–8071.

XIE C G, HUANG S M, HOYLE B S, THORN R, LENN C, SNOWDEN D and BECK M S, (1992) "Electrical capacitance tomography for flow imaging - system model for development of image reconstruction algorithm and design of primary sensors", Proceedings IEE Part G, 139, (1), pp89-98.doi: 10.1049/ip-g-2.1992.0015.