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Image Reconstruction Based on Rotatable ECT Sensor

1. Introduction

Electrical Capacitance Tomography (ECT) is a method for determination of the dielectric permittivity distribution in the interior of a subject from capacitance measurements. It is based on the use of an array of electrodes mounted around a pipe or the reactor circumference. ECT system normally consists of a capacitance sensor, a capacitance measuring unit and a control computer.

In recent years, developments in the technology have led to wide use of ECT for industrial applications for monitoring, measurement and control [1] Because of the limitation in image resolution, however, its application is still limited in a certain extent, while some applications may require higher spatial resolution.

A practicable solution to improve image resolution is to enhance the independent measurements for each frame. The number of electrode in an ECT sensor is usually 8 or 12. Increasing the number of electrodes can increase the available data and therefore possibly improve the measurement accuracy. However, a large number of electrodes would result in difficulties e.g. complicated and expensive hardware, smaller capacitance to be measured and a slower data acquisition rate [2].

Recent research has concluded that more electrodes may not necessarily give better images because of worse singularity with more electrodes [3]. In addition, the pipe wall of an ECT sensor capacity can only support a limited number of electrodes even if multi-planes of electrodes are placed. For a given diameter and electrode area, more electrodes are enwound around the pipe, longer electrodes are required, and hence the sensor will have a larger averaging area.

To overcome the problem of limited spatial resolution, an image reconstruction arithmetic is proposed in this paper based on a new type of rotatable ECT sensor.

2. Rotatable sensor

The basic scheme of the ECT system including the rotatable sensor is shown in Figure 1.

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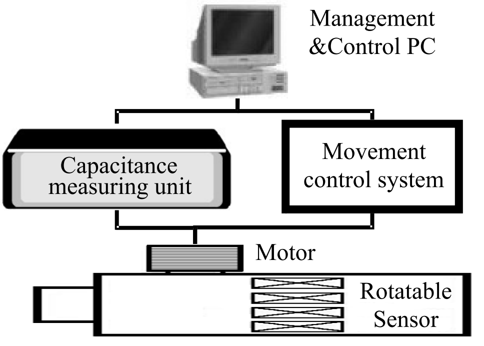


Fig. 1. Rotatable ECT system

The system is composed of a capacitance sensor, a capacitance measuring unit, a movement control unit and a control computer. The movement control unit is used to control the movement and position of the rotatable part of the sensor driven by a motor. The structure of the sensor is detailed in Figure 2. It is composed of a single plane of external electrodes. Electrodes are located on the same plane around a boundary of imaged area. The major difference is that the new sensor allows rotation of the electrodes around the object of investigation in order to increase the number of capacitance measurements with a fixed number of electrodes.

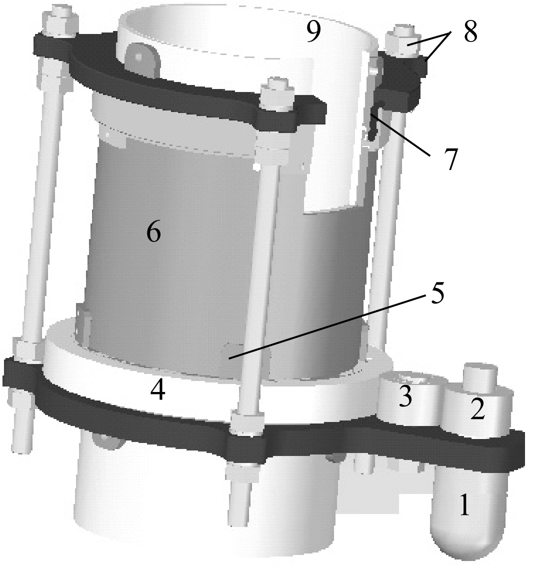


Fig. 2. The assembly view of the sensor. 1 – Stepper motor, 2 – Driver gear, 3 – Intermediate gear, 4 – Transmission gear, 5 – Support mechanism, 6 – Cylindrical tube, 7 – Bearing, 8 – Fix mechanism, 9 – Inner tube

The electrodes are mounted on an insulating tube 6, which overlays on tube 9. Between tube 6 and tube 9, sliding bearings 7 are added to reduce friction between the two tubes so that the outer tube can rotate easily. The electrodes are surrounded by an earthed outer screen to minimise the interference of external fields or objects. The rotating movement is brought along by a stepper motor.

The number of measurements for N-electrode is given by equation (1) with binomial coefficient when electrode pairs are taken without taking into account the electrode order in pair.

$$\mathrm{M} = \frac{N(N-1)}{2} \tag{1}$$

The present work is based on a sensor with 16 electrodes. The number of measurements is 120 according to equation (1). Based on this value, the number of step angles and corresponding acquisition time of the corresponding rotatable sensor can be calculated, as given in Table 1.

Table 1
Measurement analysis. n is the number of rotation positions

N-Channel ECT	Total data (N*(N-1)/2)	Rotatable ECT (16 Channels)	
		n positions	Data (n*M)
16	120	1	120
32	496	4	480
64	2080	16	1920
128	8128	64	7680
256	32640	256	30720
…	…	…	…

From Table 1, the number of new measurements is relatively close to the normal number of measurements required with a larger number of electrodes.

For a rotatable sensor with 16-channel electrodes, $4\char94^{(\alpha-1)}$ ($\alpha = 2, 3\ldots$) rotation positions are required to obtain a number of measurement set of the same order as a conventional sensor with 16α-channel electrodes.

If the measurement time of each frame is t ms, the electrodes must rotate from one position to the previous position of its right side neighbour electrode with a 22.5° angle within $p{*}t$ ms (p means the total number of angle positions). Consequently, the revolving speed of the sensor can be calculated:

$$\omega = \frac{62.5}{p*t}\ \mathrm{r/s} = \frac{3750}{p*t}\ \mathrm{r/min} \tag{2}$$

Based on Table 1, the rotation speed will be at its maximum when the number of rotation positions is 4. The available 16-electrode ECT system allows single measurement for electrode pair to be acquired in 20 ms. According to equation (2), the maximum rotation speed will be about 45 r/min when 4 step angles are set, which is easily achievable with the selected stepper motor and appropriate choice of intermediate gear diameters (see Fig. 2).

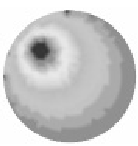
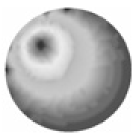
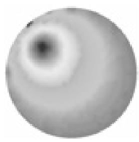
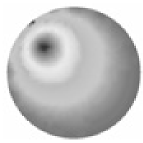
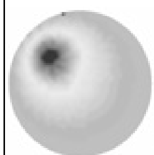
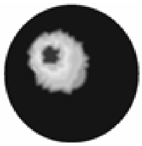
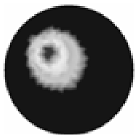
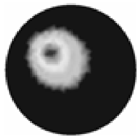
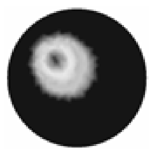
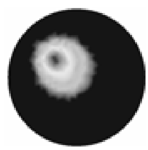
3. Rotatable ECT sensor simulation

In order to verify whether the image of new rotatable sensor is improved, a simulation based on FEM was performed. Linear forward problem was used to calculate capacitances on the basis of the actual reconstructed permittivity distribution. Linear Back Projection (LBP) was used to reconstruct the phantom image. FEM was applied to solve forward problem for the initial simulated images as well as for the phantom.

The example phantom was used to study the new approach and give some comparison between classic 32 electrodes ECT sensor and new rotatable approach. Examples of the reconstructed images are presented in the Table 2.

Table 2

Comparison of the image for the rotatable Sensor in different position with classic Sensor

 phantom	0  1				
	Pos 0	Pos 0-1	Pos 0-1-2	Pos 0-1-2-3	classic ECT 32 Electrodes
LBP					
CC	32.94 %	32.97 %	32.83 %	32.97 %	34.28%
LI	RF = 0.023 	RF= 0.0084 	RF = 0.0053 	RF = 0.004 	RF = 0.2 
CC	41.18 %	41.07 %	41.13 %	41.12 %	41.98 %

Wherein, LI– Landweber Iterations and iterations times = 20. Pos 0 means the image was reconstructed based on a 16-electrode sensor, Pos0–1–…–i means the image was reconstructed based on merging the measurement data of pos 1 to pos i of the 16-electrode sensor, CC is concentration and RF is relaxation factor.

The preliminary results showed that the increase of position of the rotatable led to good results in capacitance imaging. When the sensor rotated to the 4th position, the image quality is almost is comparable to a classical 32-electrode sensor provides.

4. Image reconstruction algorithm

Image reconstruction process in ECT can be divided into forward problem and backward problem solutions what is expressed in mathematical form on following two equations:

$$f\colon M \mapsto V \tag{3}$$

$$b\colon V \mapsto M' \tag{4}$$

where:

- f – forward problem transformation which is defined as obtaining the measurement vector for assumed material parameter distribution;
- b – backward problem transformation which is defined as obtaining the material parameter distribution from measurement vector,
- M – assumed material parameter distribution,
- M' – reconstructed material parameter distribution,
- V – measurement vector (real or simulated).

From equation (1), M equations can be obtained and the linearized and discrete form can be expressed as:

$$g = SC \tag{5}$$

where:

- S – normalized sensitivity matrix,
- g – normalized permittivity map,
- C – normalized capacitance measurement vector obtained from electrode pairs measurements.

The aim of image reconstruction for ECT is to solve the unknown g for given S according to forward problem transformation, and then by backward problem transformation, to solve the permittivity distribution S from the measured capacitance g using a set of equations. In the discrete form, it is equivalent to solve the unknown g from the known g.

The basic principle can also by be applied in the new rotatable ECT system. Suppose the sensor with N-electrode rotated p times ($p = 4\text{\^{}}\,^{(\alpha-1)}$ ($\alpha = 2, 3\ldots$)), then equation (3) can be described in the following matrix form:

$$g = S'C' \tag{6}$$

where $g \in L\times 1$, represents the grey level of a L-pixel image approximating the distribution of dielectric properties in the sensing area; $C' \in R^{pM\times 1}$ vector is interrelated to the vector of $C_k \in R^{M\times 1}$ ($k = 1\ldots, p$) where C_k represents the M capacitance measurements for the kth angle position of the rotatable ECT sensor.

The following equation can be used to rearrange pM electrode pairs:

$$\begin{aligned}&\{(m);\ m=1, M, M+1, \ldots, pM\} \Leftrightarrow \\ &\Leftrightarrow \{(p_\theta, i, j);\ p_i = 1, \ldots, p;\ i = 1, \ldots, N-1;\ j = i+1, \ldots, N\}\end{aligned} \tag{7}$$

For N electrodes pairs of the p_θth position for the ith electrode

$$C'_{p\theta,i} = \{(p_\theta, i, j);\ j = i+1, \ldots, N\} \tag{8}$$

The pM electrode pairs can be rearranged in a sequence that is equivalent to a sensor with αN-electrodes by putting equation (8) into C,

$$C = \{(C'_{p\theta,i});\ p_\theta = 1, \ldots, p; i = 1, \ldots, N\} \tag{9}$$

Finally S' in equation (6) is a $L \times pM$ matrix, the meaning of which can be described by partitioning it in the following way:

$$S' = [s_{(1)} \cdots s_M\ s_{M+1} \cdots s_{(pM)}] \tag{10}$$

where $s_{(i)}(i = 1, \ldots, pM)$ is a $L \times 1$ vector. Equation (6) can be solved using the Landweber iteration which is regarded as the most reliable iterative algorithm by many researchers:

$$g_{k+1} = g_k + \alpha_k S'^T (C' - S' g_k) \tag{11}$$

where:

g_k – image in the k^{th} step,
α_k – relaxation factor in the k^{th} step.

If the spatial sensitivity distribution S is known, the image reconstruction process is just a simple vector-matrix multiplication and iteration. Further work will focus on defining the new sensitivity matrix which takes into account the different set of capacitance measurements at the different angle positions of the rotatabl sensor.

5. Conclusion

The paper presented an image reconstruction arithmetic for a new ECT sensor with 16 in-plane electrodes considered to improve the spatial resolution. The first prototype of the sensor is being designed to be mounted on a flow apparatus (multi-phase flow, pneumatic conveyor) which is in its final stage of construction at the Computer Engineering Department of the Technical University of Lodz. According to current simulation results, it is supposed to have an image resolution comparable to the traditional sensor which provides the same number of measurement data.

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