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Miniaturized Planar Tomography for Multiphase Stagnant Sample Detection

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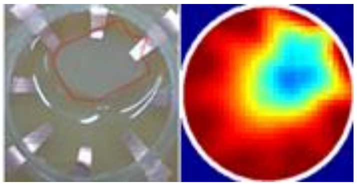
Graphical abstract



Abstract

Miniaturized device offers portability, high throughput and faster time response compared to macroscale devices. In microdevices, most of the application utilizes planar electrode for microanalysis process as it is inexpensive, highly controllable system and easy for installation. In addition, miniaturized planar sensor offers great potential for microscale medical diagnosis, chemical analysis, environmental analysis, cell culture application and single cell measurement using tomography measurement. In this project, a miniaturized planar tomography system is developed for multiphase sample detection such as liquid-solid and liquid-liquid. Eight-electrode device was fabricated on the copper plated printed circuit board (PCB) using the commercial fabrication technique. The ability of the proposed device in reconstructing images of a multiphase sample using Linear Back Projection algorithm is tested. Experimental results show that the reconstructed images closely resemble with the cross-section of the stagnant multiphase sample.

Keywords: Electrical capacitance tomography; miniaturized sensor; multiphase sample; planar tomography

1.0 INTRODUCTION

Tomography refers to the reconstruction of an internal distribution of the 2D or 3D object from multiple external viewpoints [1]. It provides real-time information on the internal state of a process without disturbing the nature of the process being examined. Various types of the sensor array can be used in tomography system to obtain cross-sectional images of an object [2] depending on their application. The possible sensing methods for process tomography are using the principle of electromagnetic radiation such as X-ray, electrical properties and acoustic. In certain cases, electrical tomography is the most attractive method for real-time imaging of industrial process due to the simplicity and the high-speed capabilities [3]. There are few electrical measurements that could be carried out to obtain data for image reconstruction. These electrical measurements are electrical impedance tomography (EIT), electrical capacitance tomography (ECT) and electrical resistivity tomography (ERT). These soft-field techniques measured the changes of the electrical field distribution within the targeted area in order to reconstruct the images of the measured substance.

In recent years, the miniaturized tomography has begun to attract researchers' attention as many potential applications offered by miniature tomography systems. The integration of miniaturized sensor array within the chip offers great potential for microscale medical diagnosis [4], chemical analysis, environmental analysis, cell culture application [5], and single cell imaging [6] using tomography measurement. The miniaturized device offers portability which allows for on-site measurement for initial sample testing.

In microdevices, most of the application utilizes planar electrode for microanalysis process [7]. Planar electrodes provide advantages such as scalability, inexpensive [8], highly controllable system [9], feasible for small particle detection and the ease of installation [10]. Planar tomography microdevices have been widely used for medical application. For instance, in the application of x-ray, gastrointestinal endoscope medical data registration, breast cancer detection, and cancer treatment monitoring. In addition, planar tomography is also applied in science and biology, especially for chemical analysis. There are a number of well-documented works related to the development of miniaturized planar tomography.

Related research of miniature electrical planar tomography device has been carried out by Sun *et al*. [11] who has reported an on chip design of impedance tomography to reconstruct the image of a biological cell. This study applied the concept of miniaturized electrical impedance tomography system where the device can provide images of two dimensional for cell culture. The developed device allows imaging of cell located at any position within the array. Besides, the developed device is useful in diagnostic and bio-medical applications cancer treatment monitoring. Also, the development of miniaturized electrical tomography for the application of inkjet technology is discussed by York *et al.* in [12]. The 8-electrode device is fabricated on a ceramic substrate using ultrasonic drilling. Electrodes are deposited around a hole, on a ceramic substrate and have an average diameter of 0.75 mm. A custom CMOS silicon chip has been designed to provide capacitance measurements, and the system has been used for preliminary studies of the dose from an inhaler and fuel injection.

In [13], it is stated that the successful applications of electrical tomography technology depend on the precision and speed of the image reconstruction algorithm. For electrical tomography, various reconstruction algorithms have been proposed such as back projection [14], iterative [15], and hybrid [16] reconstruction algorithm. At present, algorithms that are often applied to the ECT image reconstruction are the linear back projection (LBP) method [13]. This algorithm is still the most commonly used reconstruction technique as the characteristic of LBP is numerically simple and computationally fast.

In this project, a miniaturized planar electrical tomography device is developed for multiphase sample detection such as liquid-solid and liquid-liquid. The device utilizes linear back projection algorithm for image reconstruction process. An analysis on the image reconstruction process is done to inspect the repeatability and reproducibility of the miniaturized planar tomography device.

■2.0 MINIATURIZED PLANAR ECT DEVICE

2.1 ECT Planar Sensor

This project can be divided into 2 main parts which are hardware development and software development. The hardware development includes the fabrication of planar electrodes, the fabrication of miniaturized polymer based chamber and the development of the signal conditioning circuit. Meanwhile, software development focuses on the image reconstruction process.

The device is developed based on soft-field measurement using ECT measurement. The ECT device consists of a planar sensor, signal conditioning circuit as well as the control computer. This project utilizes planar electrodes for the ease of fabrication and installation. The etching technique was implemented to fabricate the 8-electrode device on the copper plated printed circuit board (PCB). Copper is used as it is a highly conductive material, easy to fabricate, and the cost of material is low. The developed device is shown in Figure 1.

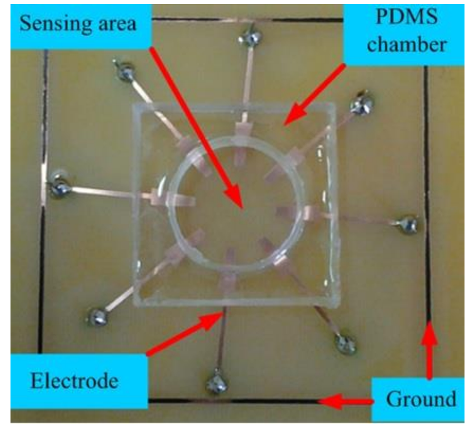


Figure 1 The fabricated miniaturized planar ECT device

Figure 1 shows the fabricated miniaturized planar ECT device. The device consists of sensor electrodes, grounding electrode and polydimethylsiloxane (PDMS) chamber. Inside the sensing area, the width and the length of each sensing electrode is 1.568 mm and 4 mm, respectively. In order to hold the sample from spreading outside the sensing area, a polydimethylsiloxane (PDMS) chamber is developed. The integration of the planar electrode sensor and the PDMS chamber form a reservoir for the process of sample detection. The details of the fabrication of the planar electrode device and the polymer-based chamber, and the development of signal conditioning system is discussed in [17].

The fan beam projection technique is used for sample detection and data acquisition in the system. In this projection technique, only one electrode is excited at one time while the remaining electrodes act as the detectors. The measurement is repeated until each of the electrodes has been excited. More data are obtained from the measurement as this technique covers most of the area in the detection chamber. As a result, higher number of measurements is obtained. Apart from that, higher number of electrode sensor also provides a higher number of measurements. Thus, it improved the resolution of the device and increased the quality of the reconstructed images. In this research, a total of 28 capacitance measurements are obtained from the fan beam projection technique. In general, the number of capacitance measurements is governed by $N(N-1)/2$, where N is the number of electrodes.

2.2 Data Acquisition and Sensitivity Map

Data Acquisition System (DAQ) comprises of the signal conditioning circuit and the main controller unit. The change of electrical parameters within the sensing area is measured by the developed signal conditioning system. The signal conditioning system utilizing AC bridge, amplifiers, low pass filter, and analog to digital converter. Signal conditioning system collects the measurement data from the sensor and then will converts the measurement reading to digital for the image reconstruction process.

In order to reconstruct images, the corresponding sensor measurement is multiplied by the sensitivity map. MATLAB simulation is used to acquire the sensitivity map and the sensitivity distribution of the sensor. For this research, a 32×32 square matrix that made up a total of 1024 pixels is used. However, 212 pixels are placed at the outer part of the sensing area and only 812 pixels are promoted to indicate the image plane. Figure 2 presents the reconstruction matrix used in this research.

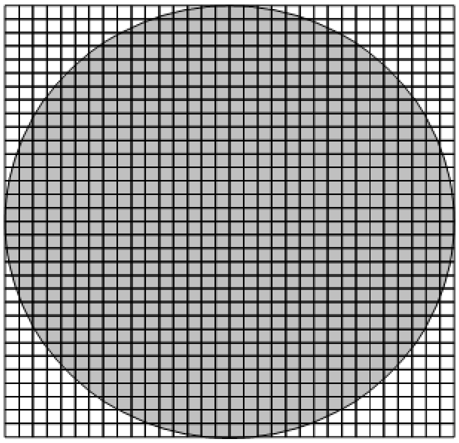


Figure 2 The sensitivity matrix of the device

2.3 Image Reconstruction

Image reconstruction is essential in any process tomography. Image reconstruction provides understandable results as it creates cross-sectional images from the projection of the data. Signal conditioning circuit collected the measurement data from the sensor and digitalised it. Next, the digital data will be sent to a control computer for the image reconstruction process.

In process tomography, the majority of the works is aimed at the application of the Linear Back Projection (LBP) algorithm [18]. LBP algorithm is preferable for image reconstruction process in this project because it is numerically simple and computationally fast. The standard LBP algorithm used in this project is provided by Protom-I Research Group (UTM). The algorithm is built using MATLAB software. Besides, in order to create the profile of simulation image reconstruction, a Graphical User Interface (GUI) is created.

A calibration of the system is done as the standard image reconstruction algorithm provided by the Protom-I Research Group (UTM) is normally used for industrial size process tomography system. System calibration is an important process before making any measurement of the system in order to obtain the reference value for each different material with different permittivity before the real measurement takes place [18]. The standard calibration procedure for an ECT system involves filling the sensor with the low permittivity material and taking a complete set of measurements. It is followed by filling the sensor with the high permittivity material and taking a complete set of measurements [19].

3.0 RESULT AND DISCUSSION

This research aims to investigate the feasibility of the miniaturized planar tomography device for microanalysis purposes. The performance of the developed device is studied through the experiments by using multiphase samples. Three different multiphase samples which are liquid-liquid, liquid-air and solid-solid are used for image reconstruction. The mixture of 'water and oil' sample, 'water and air' sample, and 'glucose and yeast' sample shown in Figure 3 is inserted into the sensing area using Terumo syringe and the signal conditioning circuit measures the capacitance between the possible electrode pair. A total of 28 capacitance measurements are obtained from the fan beam projection technique and the data is then transferred to a control computer for the image reconstruction process. Figure 3 shows the results of image reconstruction process for different multiphase samples.

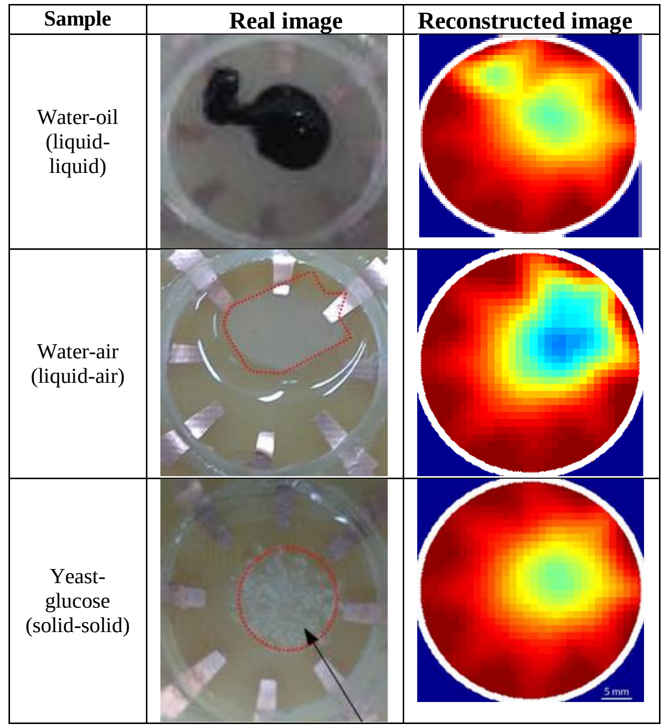


Figure 3 The reconstructed images for different multiphase sample

Based on Figure 3, it can be concluded that the standard image reconstruction algorithm developed by Protom-I Group (UTM) for 8-electrode ECT device was successfully reconstructed the images of the different multiphase sample. Although the accuracy of the reconstructed images is not 100% accurate, it is proven that the miniaturized planar tomography sensor developed is feasible in detecting the multiphase sample within the sensing area.

The percentage error of reconstructed image is calculated based on pixelizing method. The percentage error for each of the sample is calculated based on equation 1.

$$\%\ error = \frac{Real\ image - Reconstructed\ image}{Real\ image} \times 100\% \quad \textbf{(1)}$$

The percentage error in the actual and the measured readings from the three experiments are presented in Table 1.

Table 1 The comparison of actual and measured readings for each of the samples

Sample		Actual percentage (%)	Measured percentage (%)	||Error percentage|| (%)
Liquid-liquid	Water	79.31	63.79	19.57
	Oil	20.69	26.47	27.80
Liquid-air	Water	76.60	62.31	18.66
	Air	23.40	30.29	29.50
Solid-solid	Yeast	80.17	76.85	4.14
	Glucose	19.83	23.15	16.74

Table 4 shows the actual percentage of each sample that filled up the sensing area. After the image reconstruction process for each experiment is done, the percentage of each sample that filled up the sensing area is measured to determine the percentage error. Based on the results obtained, it can be concluded that the proposed device able to detect the multiphase sample in the sensing area even though it is not 100% accurate. The accuracy of the ECT devices is affected due to the factor of linear approximation and soft field characteristics of the device.

The use of soft field sensor generates an inhomogeneous field and the sensitivity distribution of the field depends on the parameter distribution [14]. The sensitivity distribution is not uniform where different locations of the electrode pairs have different sensitivity, and the sensitivity depends on the parameter distribution of the sample. The electrical properties variation within the measurement volume will distort the sensor field resulting a low spatial resolution of the reconstructed image. However, it is perfectly adequate for many industrial applications [20]. Besides, the use of planar electrode array also contributes to the non-linearity of the electrical field. The image reconstruction is done based on the average plane of the total height.

■4.0 CONCLUSION AND OUTLOOKS

In conclusion, this research has proven that planar electrodes are feasible for measuring the electrical changes in the miniaturized tomography sensor. The feasibility of the proposed device is proven as the image of the stagnant multiphase sample is successfully reconstructed using LBP reconstruction algorithm. However, the used of soft field sensor measurement results in the non-linearity of the electrical field of the proposed device that affect the accuracy of the device.

The experimental results show that the reconstructed images closely resemble with the cross-section of the multiphase sample. In this project, the feasibility of a miniaturized planar tomography device developed is tested using stagnant multiphase samples. For future works, it is recommended that a research for multiphase fluid dynamic monitoring system using miniaturized planar tomography can be done.

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