# MINIATURIZED PLANAR CAPACITANCE TOMOGRAPHY SYSTEM USING FAN BEAM PROJECTION TECHNIQUE FOR STAGNANT SAMPLES VISUALIZATION

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Specially dedicated to my lovely parents,
*Zarina Md Shariff and Azmi Md Din*

My beloved brother and sisters
*Azim, Aqilah, Aifaa, Atiqah*

And my wife
*Nazirah bt Othman*

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# ABSTRACT

Miniaturized device is an approach by integrating the laboratory function into small platform. These miniaturized devices are equipped with sensors or actuators to perform sensing, sample preparation or analysis and is well known as lab-on-chip (LOC) since 1990. The conventional miniaturized device available in the market normally provides single dimensional (1D) data at a time in most micro analysis processes. In order to obtain images from the device, cameras and microscopes are normally used. However, the size and tubing intact on the device make it difficult for cameras or optical devices to be placed within the reaction chamber to capture images that are related to the process. Processes such as cell detection and environmental analysis sometimes require two dimensional (2D) images in order to enhance the quality of analysis and data accuracy. Therefore, this research proposes to integrate tomography technique within the miniaturized device for capturing images within the device chamber in order to replace bulky optical equipment. Tomography system has been widely used in medical and industrial processes for image reconstruction. This research integrates Electrical Capacitance Tomography (ECT) system within a miniaturized device for visualization of stagnant samples via planar electrodes. This miniaturized planar tomography system consists of electrode array for the measurement of dielectric property changes within the chamber. This miniaturized device consists of 8-planar electrodes circulating the detection chamber where the dimension of each of the electrodes are 4 mm $\times$ 2 mm (length $\times$ width) printed on the circuit board. A home-made polydimenthylsiloxane chamber is fabricated and adhered on top of the electrodes to position the sample for electrical measurement and image reconstruction. Fan beam projection technique is utilized for data measurement from the miniaturized planar capacitive tomography system. The obtained data are processed using Linear Back Projection (LBP) algorithm via Matlab package for image reconstruction. Three samples: liquid-liquid, liquid-gas and liquid-solid are studied. Electrical measurement using fan beam projection is carried out and images of the samples are successfully reconstructed via LBP. Based on the obtained results, the error percentage for multiphase sample of water and air is 25% while 14.77% for solid sample of yeast and glucose. The obtained results show that the qualities of acquired images are highly depending on the voltage differences between each measurement. The amount of volume between the two materials affects the measured voltage differences. The nearer the samples to the planar electrode, the voltage differences observed are more significant. The reconstructed images using miniaturized planar capacitive tomography system for all the samples show good similarity to the camera captured images.

# ABSTRAK

Peranti bersaiz kecilad alah satu pendekatan dengan mengintegrasikan fungsi makmal kedalam pelantar kecil. Semenjak 1990, peranti kecil ini diperkenalkan dan ia bias anya dilengkapi dengan pengesan atau penggerak untuk menjalankan proses mengesan, penyediaan sampel atau analisis dan lebih dikenali sebagai *lab-on-chip* (LOC). Peranti konvensional bersaiz kecil yang terdapat di pasaran untuk analisis mikro porses biasanya menyediakan bacaan satu dimensi (1D) pada satu masa. Bagi mendapatkan imej dari peranti, kamera dan mikroskop biasanya digunakan. Walau bagaimanapun, saiz dan tiub pada peranti menyebabkan kamera dan peranti optic sukar diletakkan pada posisi peranti kecil untuk penangkapan imej bagi proses tindak balas. Untuk proses seperti pengesanan sel dan analisis alam sekitar, imej dua dimensi (2D) penting bagi meningkatkan kualiti analisis dan ketepatan data. Oleh itu, kajian ini mencadangkan untuk mengintegrasi teknik tomografi dalam peranti bersaiz kecil bagi menghasilkan imej dalam bekas peranti bagi menggantikan peralatan optik yang bersaiz besar. Sistem tomografi digunakan secara meluas dalam bidang perubatan dan proses industry bagi pembinaan semula imej. Penyelidikan ini mengintegrasikan system Tomografi Kapasitan Elektrik (ECT) ke dalam peranti bersaiz kecil bagi memerhatikan tindak balas sampel yang bertakung menggunakan elektrod satah. Sistem satah tomografi bersaiz kecil ini terdiri daripada susunan elektrod bagi mengukur perubahan dielektrik dalam bekas. Peranti bersaiz kecil ini terdiri daripada 8 elektrod satah yang mengelilingi bekas pengesan di mana dimensi setiap elektrod adalah 4 mm $\times$ 2 mm (panjang$\times$lebar) yang dicetak atas papan litar. Bekas *polydimenthylsiloxane* yang difabrikasi dalam makmal dilekatkan di atas elektrod bagi meletakkan sampel untuk pengukuran elektrik dan pembinaan semula imej. Teknik unjuran *fan beam* diguna bagi pengukuran data daripada system kapasitan tomografi satah bersaiz kecil. Data yang diperolehi diproses dengan menggunakan algoritma Unjuran *Linear Back* (LBP) melalui perisian Matlab bagi pembinaan semula imej. Tiga sampel : cecair-cecair, cecair-gas dan cecair-pepejal dikaji. Pengukuran elektrik menggunakan unjuran *fan beam* dijalankan dan imej sampel dibina semula dengan jayanya melalui LBP. Daripada keputusan yang diperolehi, peratus ralat bagi sampel pelbagai fasa iaitu air dan udara adalah 25% sementara peratusan ralat untuk sampel pepejal yis dan glukosa adalah 14.77%. Keputusan yang diperolehi menunjukkan bahawa kualiti imej yang diperolehi bergantung kepada perbezaan voltan di antara setiap pengukuran. Isipadu antara dua bahan memberi kesan kepada perbezaan voltan yang diukur dan semakin dekat sampel dengan elektrod satah, perbezaan voltan yang ketara diperolehi. Pembinaan semula imej menggunakan sistem kapasitan tomografi satah bersaiz kecil bagi semua sampel menunjukkan persamaan dengan imej yang diambil dengan menggunakan kamera.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AC | - | Alternative Current |
| CMOS | - | Complementary Metal Oxide Semiconductor |
| CT | - | Clinical Tomography |
| DAS | - | Data Acquisition System |
| ECT | - | Electrical Capacitance Tomography |
| EF | - | Electrical Field |
| EIT | - | Electrical Impedance Tomography |
| EMT | - | Electromagnetic Tomography |
| ERT | - | Electrical Resistance Tomography |
| IC | - | Integrated Circuit |
| LBP | - | Linear Back Projection |
| LCR | - | Inductance, Capacitance And Resistance |
| LED | - | Light Emitting Diode |
| LOC | - | Lab-On-Chip |
| MATLAB | - | Matrix Laboratory |
| MIT | - | Magnetic Induction Tomography |
| MRI | - | Magnetic Resonance Imaging |
| NMR | - | Nuclear Magnetic Resonance Tomography |
| PCB | - | Printed-Circuit-Board |
| PDMS | - | Polydimethylsiloxane |
| PET | - | Positron Emission Tomography |
| V | - | Voltage |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $\ell$ | - | Length of the electrode |
| $C_f$ | - | Feedback capacitor |
| $R_f$ | - | Feedback resistor |
| $^\circ$ | - | Degree |
| $a$ | - | Haft gap between electrode |
| $C$ | - | Capacitance |
| $\mathcal{E}_0$ | - | Electric constant |
| $\mathcal{E}_r$ | - | Dielectric constant |
| $f$ | - | Frequency |
| k$\Omega$ | - | Kilo-ohm |
| kHz | - | Kilo-hertz |
| $R_X$ | - | Receiver |
| $T_X$ | - | Transmitter |
| V | - | Voltage |
| $w$ | - | Width of the electrode |
| $\sigma$ | - | Standard deviation |

# LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Tomography was originated from the Greek word “Tomos” in 1935’s. Tomography is defined as the slice of image from the cross section of an object. Oxford dictionary defines tomography as the method for demonstrating a cross section of human body or any solid form object via X-rays or ultrasound. In process tomography, there are two types of imaging system measurement which are non-intrusive and intrusive tomographic. The selection of the tomography imaging system depends on the suitability of the proposed sample which does not disturb the characteristic and nature behavior of the sample and also the capability of the system for measurement.

Tomography is divided into two categories; the electrical tomography method and the radiation-based tomography method. The electrical tomography aredivided into three types which are the electrical impedance tomography (EIT), electrical capacitance tomography (ECT) and electromagnetic tomography (EMT). Among these types, ECT offers advantages such as easy design and fabrication, flexibility in excitation and low cost [1-4] at which cause ECT one of the widely used system in the industry.

In medical industry, tomography concept was used for diagnostic purposes [5]. The tomography concept was applied for the first time in 1980’s using x-rays imaging to observe the cross section images of human body non-invasively. The images showed the cross section of a specific area of the scanned part of the human body to allow investigation of the area during operation procedures. Besides X-ray, other applications in medical utilized the tomography concept are Magnetic resonance imaging (MRI) [6-8] and Computed tomography (CT) scan [8]. Both of the instruments share the same objective which is to obtain the image of scanned area.

Aside from medical industry, industrial process as well is utilizing tomography widely for imaging purposes [2]. Process tomography helps the industry to monitor the compositions of materials flow within a closed pipeline [9-11].

Based on the applications of tomography in the medical and process industry nowadays, both sectors have shown interests in using tomography in a large scale as their samples are huge in sizes and high volume. However, recent interest has centred on the small scale detection by using miniaturizing technology which has attracted research attention for environmental, biomedical and chemical analysis. For instance, in environmental sample analysis, the image of the sample usually is observed using microscope for small sample detection and analysis. This concept however is not appropriate to on-site measurement. Therefore, the motivation of miniaturizing tomography is the first step to explore the needs and requirement for small sample detection [12].

The miniaturized approach has been achievable by using Lab-on-chip (LOC). LOC is defined as the integration of laboratory functions into small devices. The concept was introduced by Manz in 1990’s [13]. LOC is used for small scale or micro detection and analysis. Many advantages of LOC can be listed for example high throughput, portable and lightweight [14]. Besides that, most of LOC utilizes planar electrodes due to the ease of fabrication and installation [5, 14, 15].

Nevertheless, most of micro sensors only provide single dimensional data (1D) [12, 16, 17]. For environmental and biomedical measurement and analysis, more information are needed for detailed analysis for example 2D image. Thus, by implementing the tomography in the LOC devices, the image of the measurent sample can be obtained [5].

## 1.2 Problem Statement

Mobility device is important for many environmental and bioanalysis. However, most of the current equipment that assist in initial analysis are normally located in the laboratory. One of the initial analysis is to visualize the samples using optical scope such as microscope which are not mobile. In environmental sample analysis, some of the samples need to be measured on-site as to confirm the correctness of the sample collection. Other than that, some of the sample degrades during the transferring period from the site to the laboratory. Besides that, environmental issues such as temperature, vibration and chemical reaction will affect the sample's quality. Therefore, a portable mobile sensor is important for an on site sample measurement.

In addition, most of the detections for miniaturization devices are normally providing 1D data for most microanalysis [12, 16-18]. 1D data is normally illustrated in a graph form for data analysis. However, for cell detection, biomedical sample analysis and multiphase sample properties, 2D tomograms image is crucial for visualizing the real image of sample. From the tomograms, the monitoring of sample can be easily done. Therefore,a sensor designed by integrating the tomography concept into miniature device to reconstruct 2D tomograms for small scale sample is needed.

The accuracy of miniaturization measurement is important for microanalysis. Most of the miniature devices provide a single data as it is a challenge to introduce more microsensors within the microdevice to provide more accurate results that represent the whole sample. Therefore, there is a need for a tomography system with fan beam projection technique, for example in order to be able to provide data that cover the most area of the detection chamber. In fan beam projection technique, measurements are repeated for each electrode until all electrodes are excited as transmitters. This way, more data are acquired and more accurate estimation of process measurement can be made.

## 1.3 Research Objectives

The aim of the research is to develop the miniaturized planar tomography sensor which can be realized by achieving the objectives below:

1. To investigate the feasibility of planar electrode for miniaturized electrical capacitance tomography system
2. To develop, fabricate and characterize the miniature device utilizing electrical capacitance tomography measurement methods
3. To reconstruct 2D images of multiphase experimental samples

This research investigates and studies the feasibility of miniaturized planar sensor in process tomography for conventional tomography system. The development of the planar sensor is based on soft field measurement using electrical capacitance tomography. The hardware is done through fabrication, characterization and signal conditioning circuit. The image reconstruction algorithm is performed by using linear back projection (LBP) provided by Protom-i Research Group, UTM. Three different samples were used for image reconstruction such as a mixture of “water and oil” and multiphase samples of “water and air” and “glucose and yeast”.

## 1.4 Scope of the Research

This research investigates and studies on the feasibility of electrode sensors in miniaturized planar tomography chip. Soft field measurement is proposed by using electrical capacitance measurement as this measurement is sensitive in multiphase of different permittivity.

This project consists of hardware development, signal conditioning and image reconstruction. The hardware development consists of fabrication of the planar electrodes and miniaturized polymer-based chamber. The planar electrode is fabricated using printed circuit board (PCB) follow the conventional PCB fabrication method due to low cost factor. Meanwhile, the master template is fabricated using 3D printer due to low cost of printing material and easy for casting the prepolymer. The polydimenthylsiloxane (PDMS) is used for chamber material as the material is low cost and easily formed in small device fabrication where the material is widely used in LOC device. Signal conditioning circuit is developed to measure the changes of the electrical parameters within the chamber. Physical test and electrical characterization are done to investigate the feasibility of the device for miniaturized tomography measurement. The measurement using signal conditioning system is done in the laboratory as the supply source required in order to operate the instrument such as function generator and oscilloscope.

The image of sample is reconstructed using LBP for image reconstruction. The LBP algorithm is modified from 16 based electrodes to 8 based electrodes. As the LBP image reconstruction algorithm are normally used for industrial-sized process tomography system, calibration of miniaturized devices and samples are done via system calibration. Mixture of sample with single and multiphases are used for the testing experiment of the developed device. The reconstructed image is compared to the real image of sample for image comparison by calculating the percentage error between the real and reconstructed image based on pixelizing/gridding method. Simulation is done for data analysis.

## 1.5 Thesis Structure

The thesis consists of six chapters which this chapter discusses on the introduction, problems statement, research objective, and scope of the research. The introduction basically discussed on the need of the research, the application of the research, the benefit of the research and lastly the challenges or the obstacle to achieve the objective of the research.

Chapter 2 reviews the previous research on the tomography imaging technique and the sensors used for the data acquisition in tomography. Besides that, the lab-on-chip application, fundamental concept, theories and advantages also been reviewed.

Chapter 3 presents the sensor fabrication and characterization. The assembly proceeding of the sensors and the sensing chamber are explained in this chapter. Besides that, the characterizations and feasibility test of the assembled device are discussed.

In chapter 4, the signal conditioning of the sensor is shown and discussed. The optimum frequency and voltage are given and result was discussed. The experimental to prove the feasibility of the signal conditioning was conducted and the result was analyzed.

Chapter 5 mainly discusses on the result and analysis. There are three samples used in the experiment such as the combination of water and oil, water and air and glucose and yeast. Experimental result is validated through simulation result.

Chapter 6 concludes the findings of the research as well as future work. The recommendation to continue and improve the system in this research is stated in chapter 6.

# REFERENCES

[1] Yu, C., Jian, Z., and Deyun, C. Two-phase flow parameters measurement and Gauss-Newton image reconstruction algorithm for Electrical Capacitance Tomography.*2009 International Conference on Industrial Mechatronics and Automation*. May 15-16, 2009. Chengdu: IEEE,2009. 192 - 195.

[2] Yang, W. Tomographic Imaging based on Capacitance Measurement and Industrial Applications. *2007IEEE International Workshop on Imaging Systems and Techniques* . May 5, 2007. Krakow, Poland: IEEE,2009.1 - 6.

[3] Yu, C., Jian, *Z*., and Deyun, C. Two-phase Flow Parameters Measurement and Image Reconstruction for Electrical Capacitance Tomography. *2008 International Workshop on Education Technology and Training & 2008 International Workshop on Geoscience and Remote Sensing*. Dec 21-22, 2008. Shanghai: IEEE,2008. 680 – 684.

[4] Klos, M., and Smolik, W. T. Single channel electrical capacitance tomograph for dynamic process visualization. *Imaging Systems and Techniques (IST), 2011 IEEE International Conference*. May 17-18, 2011. Penang: IEEE,2011. 133-136.

[5] Sun, T., Tsuda, S., Zauner, K. P., and Morgan, H. (2010). On-chip electrical impedance tomography for imaging biological cells. *Biosensors and Bioelectronics Journal*, 25(5), 1109-1115.

[6] Cardillo, F A., Starita, A., Caramella, D., and Cilotti, A. A neural tool for breast cancer detection and classification in MRI. *Engineering in Medicine and Biology Society, 2001. Proceedings of the 23rd Annual International Conference of the IEEE*. October 25-28, 2001. Istanbul, Turkey: IEEE,2001. 2733 - 2736.

[7] Li, G., Chen, R., Hao, L., and Lin, L. Three dimensional MREIT for breast cancer detection on open MRI scanners. *Proceeding of the IEEE International Conference on Information and Automation in Information and Automation (ICIA)*.June 6-8, 2012. Shenyang, China: IEEE, 2012. 446-450.

[8] Seo, Y., Kurhanewicz, J., Franc, B. L., Hawkins, R. A., and Hasegawa, B. H. Improved prostate cancer imaging with SPECT/CT and MRI/MRSI. *Nuclear*

*Science Symposium Conference Record*. December 5,2004.IEEE, 2004,. 2402-2406.

[9] Li, X., Huang, Z., Wang, B., and Li, H. A new method for the on-line voidage measurement of gas-oil two-phase flow. IEEE *International Instrumentation and Measurement Technology Conference*. May 12-15, 2008. Victoria, Vancouver Island, Canada: IEEE, 2008. 1091-5281.

[10] Bolton G. T., Korchinsky, W. J., and Waterfall, R. C. (1999). Imaging Immiscible Liquid-Liquid Systems by Capacitance Tomography. *Chemical Engineering Research and Design*, 77(8). 699-708.

[11] Jeanmeure, L. F. C., Dyakowski, T., Zimmerman, W. B. J., and Clark, W. (2002). Direct flow-pattern identification using electrical capacitance tomography. *Experimental Thermal and Fluid Science* 26(6-7), 763–773.

[12] Evans, I., and York, T. (2004). Microelectronic capacitance transducer for particle detection. *IEEE Sensors Journal*, 4(3), 364-372.

[13] Manz, A., Graber, N., and Widmer, H. M. (1990). Miniaturized total chemical analysis systems: A novel concept for chemical sensing. *Sensors and Actuators: B. Chemical*, 1(1-6), 244-248.

[14] Pai, R. S., Roussel, T. J., Crain, M. M., Jackson, D. J., Baldwin, R. P., Keynton, R. S., Naber, J. F., and Walsh, K. M. Lab-on-a-chip systems with three dimensional microelectrodes. *Proceedings of the 3rd Annual International IEEE EMBS Special Topic Conference on Microtechnologies in Medicine and Biology*. May 12-15, 2005.Kahuku, Oahu, Hawaii: IEEE, 2005. 18 – 21.

[15] Miled, M. A., and Sawan, M. Electrode robustness in artificial cerebrospinal fluid for dielectrophoresis-based LoC. *Annual International Conference of the IEEE* EMBS.August 8 - September 1, 2012. San Diego, CA: IEEE, 2012. 1390-1393.

[16] Miled, M. A., and Sawan, M. (2012). Dielectrophoresis-Based Integrated Lab-on-Chip for Nano and Micro-Particles Manipulation and Capacitive Detection. *IEEE Transactions on Biomedical Circuits and Systems*. 6(2),120-132.

[17] Sippola, C. B., and Ahn, C. H. A ceramic capacitive pressure microsensor with screen-printed diaphragm. *Sensors, 2005 IEEE*. Oct. 30 -Nov. 3 ,2005. Irvine, CA:IEEE,2005. 1271-1274.

[18] Cao, Y., Zhu, Y., Rong, G., Lin, Z., Wang, G., Gu, Z., and Sawan, M. (2012). Efficient Optical Pattern Detection for Microcavity Sensors Based Lab-on-a-Chip. *IEEE Sensors Journal*, 12(6). 2121 - 2128.

[19] Yang, W. Q. and Peng, L. (2003). Image reconstruction algorithms for electrical capacitance tomography. *Measurement Science and Technology,* 14(1).

[20] Beck, M. S., and Williams, R. A. (1996). Process tomography: a European innovation and its applications. *Measurement Science and Technology,* vol. 7, 215.

[21] Xie, C. G., Reinecke, N., Beck, M. S., Mewes, D., and Williams, R. A. (1995). Electrical tomography techniques for process engineering applications. *The Chemical Engineering Journal and the Biochemical Engineering Journal,* vol. 56, 127-133.

[22] Kak A., and Slaney, M. *Principles of computerized tomographic imaging*. 1988: IEEE Press (C) Institute for Electrical and Electronic Engineers.

[23] Rit, S., Sarrut, D., and Desbat, L. (2009). Comparison of Analytic and Algebraic Methods for Motion-Compensated Cone-Beam CT Reconstruction of the Thorax. *IEEE Transactions on* medical imaging, 28(10), 1513-1525.

[24] Andersen, A. H. (1989). Algebraic Reconstruction in CT from Limited Views. *IEEETransactions On Medical Imaging,* 8(1), 50 – 55.

[25] Yang, X., Ommen, J. R., and Muddle, R. F. (2014). Comparison of genetic algorithm and algebraic reconstruction for X-ray tomography in bubbling fluidized beds. *Powder Technology,* vol. 253, 626-637.

[26] Hoyle, B. S., and Xu, L. A. Chapter 8 - Ultrasonic sensors," in *Process Tomography,* Williams R. A. and Beck M. S., Editors. 1995, Butterworth-Heinemann: Oxford.p. 119-149.

[27] Rahim., R. A., Rahman, M. H. F., Nyap, N. G., and San, C. K. (2004). On monitoring of liquid/gas flow using ultrasonic tomography. *Jurnal Teknologi*,40(D), 77-88.

[28] Mochizuki, H., Tashiro, M., Tagawa, M., Kano, M., Itoh, M., Okamura, N., Watanabe, T., and Yanai, K. The effects of a sedative antihistamine, d-chlorpheniramine, on visuomotor spatial discrimination and regional brain activity as measured by positron emission tomography (PET). *human psychopharmacology,* vol. 17, 413-418.

[29] Kovalchuk, Y., and Callaghan, V. A Self-Organizing System for Online Maintenance of a Living Organism. *2010 Sixth International Conference on Intelligent Environments (IE),* July 19-21, 2010. 283 - 288.

[30] Sallehuddin Bin Ibrahim (2000). *Measurement of gas bubbles in a vertical water column using optical tomography*. PhD. Sheffield Hallam University.

[31] Davidson, J. L., Ruffino, L. S., Stephenson, D. R., Mann, R., Grieve, B. D., and York, T. A. Three-dimensional electrical impedance tomography applied

to a metal-walled filtration test platform. *Measurement Science and Technology*, vol. 15, p. 2263, 2004.

[32] Bahrani, N., and Adler, A. 2.5D finite element method for electrical impedance tomography considering the complete electrode model. *2012 25th IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*. April 29 - May 2, 2012. Montreal, QC: IEEE,2012. 1 - 6.

[33] Brown, B. H. (2001). Medical impedance tomography and process impedance tomography: a brief review. *Measurement Science and Technology*, vol. 12, 991–996.

[34] Ruzairi Abdul Rahim (1996). *A tomographic imaging system for pneumatic conveyors using optical fibres*. PhD. Sheffield Hallam University.

[35] Rahim, R. A., Chan, K. S., Pang, J. F., and Leong, L. C. A hardware development for optical tomography system using switch mode fan beam projection. *Sensors and Actuators A: Physical*.120(1): 277-290.

[36] Vedam, S. S., Keall, P. J., Docef, A., Todor, D. A., and Kini, V. R. (2004). Predicting respiratory motion for four-dimensional radiotherap. *Medical Physic Journal* 31(8), 2274-2283.

[37] Fan, Z., and Gao, R. X. A new sensing method for Electrical Capacitance Tomography. *Instrumentation and Measurement Technology Conference (I2MTC)*. May 3-6, 2010. Austin, TX: IEEE,2010. 48 – 53.

[38] York, T. A., Phua, T. N., Reichelt, L., Pawlowski, A., and Kneer, R. (2006). A miniature electrical capacitance tomograph. *Measurement Science and Technology*, vol. 17, 2119–2129.

[39] Tapp, H. S., and Williams, R. A. (2000). Status and applications of microelectrical resistance tomography. *Chemical Engineering Journal*. 77(1-2): 119-125.

[40] Ghallab, Y. H., and Badawy, W. Techniques for biocells sensing, detection and characterization. Proceedings. Of the 2005 International Conference onMEMS, NANO and Smart Systems. July 24-27, 2005. Washington, DC, USA: IEEE,2005. 402 – 405.

[41] Qaiser, A. (2010). Designing a Capacitive Sensor using COMSOL.

[42] Gamio, J. C. (2002). A comparative analysis of single- and multiple-electrode excitation methods in electrical capacitance tomography. *Measurement Science and Technology*,13(12), 1799.

[43] Hahn, G., Just, A., Dittmar, J., and Hellige, G. Systematic errors of EIT systems determined by easily-scalable resistive phantoms. *Physiological Measurement*, 29(6), S163.

[44] Wang, H., Fedchenia, I., Shishkin, S. L., Finn, A., Smith, L., and Colket, M. Image reconstruction for electrical capacitance tomography exploiting sparsity.*Future of Instrumentation International Workshop (FIIW)*.October 8-9, 2012. Gatlinburg, TN: IEEE, 2012. 1 – 4.

[45] Somerville, A.,Evans, I., and York, T. Preliminary Studies Of Planar Capacitance Tomography. *1st World Congress on Industrial Process Tomography*. April 14-17, 1999. Buxton, Greater Manchester: Virtual Centre for Industrial and Process Tomography (VCIPT),1999. 522-529.

[46] Reyes, D. R., Iossifldls, D., Auroux, P. A., and Manz, A. (2002). Micro Total Analysis Systems. 1. Introduction, Theory, and Technology. *Analytical Chemistry*, vol. 74, 2623-2636.

[47] Oh, D. J., Jung, J. H., Kang, J. Y., and Lee, S. H. A disposable polymer waveguide lab-on-a-chip for real-time detection of protein c using evanescent wave. *IEEE SENSORS 2010 Conference*. Nov. 1-4, 2010. Kona, HI: IEEE, 2010, 1605 - 1608.

[48] Lee S. H., Jun S. B., Ko, H. J., Kim S. J., and Park, T. H. (2009). Cell-based olfactory biosensor using microfabricated planar electrode. *Biosensors and Bioelectronics*, 24(8), 2659-2664.

[49] Elmy JohanaMohamad (2012). *A segmented capacitance tomography for visualising material distributions in pipeline conveying crude palm oil*. Ph.D. Universiti Teknologi Malaysia.

[50] Chan Kok San (2002). Real time image reconstruction for fan beam optical tomography system. Master Degree. Universiti Teknologi Malaysia.

[51] Rahim, R. A., Rahiman, M. H. F., Leong, L. C., Chan, K. S., and Pang, J. F. (2008). Hardware Implementation of Multiple Fan Beam Projection Technique in Optical Fibre Process Tomography. *Sensors*, 8(5), 3406-3428.

[52] Gamio, J. C., Castro, J., Rivera, L., Alamilla, J., Garcia-Nocetti, F., and Aguilar, L. (2005). Visualisation of gas–oil two-phase flows in pressurised pipes using electrical capacitance tomography. *Flow Measurement and Instrumentation*,16(2-3), 129-134.

[53] Sawan, M., Miled, M. A. and Ghafar, Zadeh. E. CMOS/microfluidic Lab-on-chip for cells-based diagnostic tools.*2010 IEEE Annual International Conference in Medicine Engineering and Biology Society (EMBC)*. Aug. 31-Sept. 4, 2010. 5334 - 5337.

[54] Elbuken, C., Glawdel, T., Chan, D., and Ren, C. L. (2011). Detection of microdroplet size and speed using capacitive sensors. *Sensors and Actuators A: Physical*, 171(2). 55-62.

[55] Rahim, R. A., Rahiman, M. H. F., and Taib, M. N. M. Non-invasive ultrasonic tomography: Liquid/gas flow visualization. *1st International*

*Conference on Computers,Communications, & Signal Processing with Special Track on Biomedical Engineering*. Nov 14-16, 2005. Kuala Lumpur, Malaysia: IEEE,2005. 243 - 247.