

OPTICAL TOMOGRAPHY SYSTEM USING CHARGE-COUPLED DEVICE

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Specially dedicated to my husband, *Jemmy*, for his helps, supports and encouragement during the challenges of graduate study and life. This work also dedicated to my mother, parents in law and in memory of my late father, *Jamaludin*.

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## ABSTRACT

This research presents an application of Charge-Coupled Device (CCD) linear sensor and laser diode in an optical tomography system. Optical tomography is a non-invasive and non-intrusive method of capturing a cross-sectional image of multiphase flow. The measurements are based on the final light intensity received by the sensor and this approach is limited to detecting solid objects only. The aim of this research was to analyse and demonstrate the capability of laser with a CCD in an optical tomography system for detecting different types of opaque objects in crystal clear water. The image reconstruction algorithms used in this research were filtered images of Linear Back Projection algorithms. These algorithms were programmed using LabVIEW programming software. Experiments in detecting solid and transparent objects were conducted, including experiments of rising air bubbles analysis. Based on the results, statistical analysis was performed to verify that the captured data were valid compared to the actual object data. The diameter and image of static solid and transparent objects were captured by this system, with 320 image views giving less area error than 160-views. This suggests that high image view resulted in high resolution image reconstruction. A moving object's characteristics such as diameter, path and velocity can also be observed. The accuracy of this system in detecting object acceleration was 82%, while the average velocity of rising air bubbles captured was 0.2328 m/s. In conclusion, this research has successfully developed a non-intrusive and non-invasive optical tomography system that can detect static and moving objects in crystal clear water.

## ABSTRAK

Kajian ini membentangkan penggunaan Peranti Terganding Cas (CCD) dan laser di dalam sistem tomografi optik. Tomografi optik adalah satu kaedah tomografi yang tanpa rejah dan tidak invasif dalam merakam imej keratan rentas pelbagai aliran fasa bendalir. Kaedah pengukuran ini adalah berdasarkan kepada keamatan cahaya akhir yang diterima oleh peranti pengesan dan pendekatan ini adalah terhadap untuk mengesan objek padu sahaja. Tujuan kajian ini dijalankan untuk menganalisis dan demonstrasi terhadap keupayaan laser dengan CCD dalam sistem tomografi optik untuk mengesan perbezaan objek mengikut kelegapan yang wujud di dalam air jernih. Algoritma pembinaan semula imej yang digunakan dalam kajian ini adalah daripada imej Pancaran Kembali Linear yang ditapis. Algoritma ini diprogramkan menggunakan perisian pengaturcaraan LabVIEW. Ujikaji dalam mengesan objek padu dan telus termasuk ujikaji kenaikan buih udara dijalankan dan dianalisis. Berdasarkan hasil ujikaji, analisis statistik dilakukan untuk mengesahkan data yang dirakam adalah sama dengan data objek yang diketahui. Diameter serta imej objek padu dan telus yang berkedudukan statik yang dirakam oleh sistem ini menunjukkan bahawa 320 paparan imej memberi ralat kawasan yang kurang berbanding 160 paparan imej. Ini menyatakan bahawa bilangan paparan imej yang tinggi menghasilkan imej yang beresolusi tinggi. Ciri-ciri objek yang bergerak seperti diameter, cara laluan dan halaju boleh diketahui. Ketepatan sistem ini dalam mengesan pecutan objek adalah 82%, sementara itu, halaju purata kenaikan gelembung udara yang berjaya dirakam adalah  $0.2328 \text{ ms}^{-1}$ . Kesimpulannya, kajian ini telah berjaya membangunkan sistem tomografi optik yang tanpa rejah dan tidak invasif dalam mengesan objek statik dan bergerak di dalam air yang jernih.

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**LIST OF ABBREVIATIONS**

ANOVA	-	Analysis of Variance
CCD	-	Charge Coupled Device
CT	-	Computed Tomography
HAZ	-	Heat Affected Zone
HOV	-	Homogeneity of Variance Test
LBP	-	Linear Back Projection
LED	-	Light Emitting Diode
OPT	-	Optical Tomography System
ROG	-	Read Out Gate
SPECT	-	Single Photon Emission Computed Tomography

**LIST OF SYMBOLS**

$A$	-	Area
$B$	-	Magnetic field
$D, d$	-	Diameter
$E$	-	Tangential electric field
$h$	-	Height
$l$	-	Length
$M$	-	Sensitivity map
$N$	-	Refraction index
$N$	-	Total number of pixels
$Q$	-	Flow rate
$r$	-	Radius
$rx$	-	Receiver
$S$	-	Sensor loss
$T$	-	Time
$tx$	-	Transmitter
$V$	-	Voltage
$w$	-	Width
$\theta$	-	Angle
$\alpha$	-	Absorption coefficient
$\emptyset$	-	Diameter

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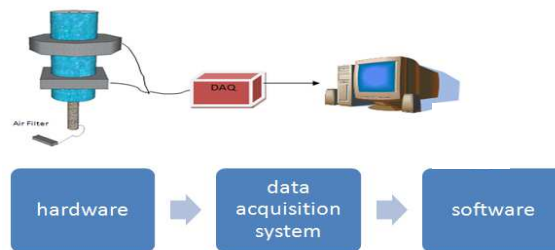
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## CHAPTER 1

### INTRODUCTION

#### 1.1 Research Background

The tomography method has been used since 1950 in medical fields and spread into industry by 1990 [1]. The tomography system is suitable to apply for non-invasive and non-intrusive monitoring, especially in industries that deal with multiphase flow. Figure 1.1 shows the basic block diagram for a tomography system.



**Figure 1.1:** Basic block diagram for tomography system

Petroleum refining systems, textile and fabric industries, oil and gas pipeline systems, geothermal wells, steam generation in boilers and burners, and steam condensation all deal with two-phase flow which is in the form of gas bubbles and liquid [2]. Engineers need to monitor the condensation process or the distribution of steam bubbling to avoid any damage occurring in the high cost and high maintenance of their system. The existence of miniature gas bubbles of hydrocarbons, for example, will affect the temperature and viscosity of the flowing



mixture. The increasing number of smaller bubbles will form an elongated Taylor bubble. As a result, the surrounding liquid will be pushed by the gases to the sides of the pipe wells and damage the system [2]. In geothermal well processing systems, increase of the water temperature will cause an increase in the number of air bubbles. Unfortunately, this will affect the fluid pressure. Therefore, continuous monitoring by engineers is very important [2]. The gas percentage in the liquid medium, gas flow rate, appearance and disappearance of gases, shape of gases, and their diameters are imperative information for monitoring and process control. The available gas detectors use intrusive and invasive techniques such as impedance probes, optical fibre probes, ultrasound Doppler and isokinetic probes. For non-intrusive and non-invasive techniques, examples of gas bubble detectors are pressure transducers, the gamma ray density gauge technique, laser technique and tomography technique. Optical tomography (OPT) is the best approach because this method consists of hard field sensors [3] where the sensor does not depend on the changes of conductivity or permittivity of the subjects that are being analysed. The OPT system provides a good spatial resolution, where it can capture a very detailed image without making the pixels visible. OPT also provides a high-speed data capture system and it is suitable for online monitoring system applications.

The aim of this research project is to build an OPT system using the combination of a Charge-Coupled Device (CCD) linear sensor and laser diodes with LabVIEW software to detect multiphase flow. The basic principle of the OPT system with CCD is similar to the Single Photon Emission Computed Tomography (SPECT) concept, where source photons of SPECT gamma are converted into visible light. Then, this visible light will be converted into electrical signals by a photomultiplier [4]. The difference between these two systems is their application and the type of sensors used. SPECT is mostly used for medical purposes and requires a contrast agent [4]. SPECT uses a gamma ray as the transmitter and it exposes the patient to radiation. However, the suggested OPT system promises a non-intrusive, non-invasive and non-hazardous radiation system for online industrial inspection of multiphase flow measurement. This hardware development is capable of detecting opaque and transparent objects without the help of a contrast agent, which can disturb the stability of multiphase flow. Qualitative and quantitative

analyses were done using LabVIEW and Minitab software. Minitab software is used for statistical analysis, while LabVIEW programming has been developed to measure the object diameter and velocity for offline data, and to produce a cross-sectional pipeline image for real-time data. Linear Back Projection (LBP) and filtered image algorithms were introduced and applied on 160 and 320 image views reconstruction analysis. The image captured is displayed in 64 x 64 image resolution but in different numbers of views. A view is a term for the single combination of emitter and detector which are aligned in a parallel array known as projection [5]. The main reason for selecting 160 views and 320 views to study is to verify the statement that a higher number of sensors will generate a better quality image reconstruction [6].

## **1.2 Problem Statement**

Optical tomography systems are widely applied in detecting solid objects compared to transparent objects. Research that uses chromatic light, such as a Light Emitting Diode (LED), has difficulty in detecting transparent objects. A transparent object will act as a prism that can diffract white light into its basic light spectra. This will result in inaccurate data being obtained. A laser diode is the best transmitter because it is a monochromatic light source.

Research was conducted using a laser diode with a Charge-Coupled Device (CCD) linear sensor in the tomography field to detect solid objects. The system is capable of measuring the solid object's diameter and velocity. Problems that occurred in this research are that the low data sampling (250 kHz sample per second for the whole system) will cause data losses. This will give inaccurate data measurement because the diameter values are based on the total effective number of CCD pixels. A correction factor should be applied to compensate the inaccurate data measurement. The previous research also claimed that a single plane of the CCD OPT system was able to capture the object's velocity based on the length of the CCD pixel. Unfortunately, this technique gives inaccurate results, where different object sizes will have different time intervals and distances.

Previous OPT system researchers are keen to use a fast operational speed monochromatic transmitter such as a laser diode that will apply a switching mode technique. This method captures a single fraction of a view in a measurement frame. Delay in alternation from one projection to the next projection will increase the time per scan for a full measurement frame. The probability of data losses, especially in moving object research, is very high. Simultaneous projection is proposed to overcome the mentioned problems.

### **1.3 Research Objectives**

This research project consists of three main objectives, as listed below:

- i. To investigate and analyse the appropriate OPT system modelling, with a correction factor to overcome data loss, and image reconstruction algorithms that will match with the CCD linear sensors and laser diodes in producing high quality image reconstruction.
- ii. To design and develop a dual-plane OPT system to enable more solid research for object velocity data. LabVIEW programming for real-time image reconstruction of a cross-sectional pipeline system and offline measurement are developed.
- iii. To conduct a number of experiments with static objects (solid, glass rod and transparent hollow straw) and moving objects (air bubbles) to prove the ability of the OPT with CCD sensors system to capture and analyse the data of objects in transparent liquid.

### **1.4 Research Scopes and Limitations**

The scope of this research project can be divided into four main parts. The first is to analyse and develop the optical system and image tomography modelling that is appropriate for the CCD linear sensors and their light sources.

Then, hardware and software developments based on the above modelling are involved. Early stage experiments concerned with analysing the suitability of LEDs and laser diodes with CCD linear sensors were conducted. After selection of a laser as the most suitable sensor for the CCD, prototypes of the OPT system were developed as a guideline for a fixed hardware fabrication. During this stage, basic LabVIEW programming was developed for offline and online measurement based on improved previous research on mathematical modelling.

Once the fixed hardware and advanced LabVIEW programming were developed, a series of experiments were conducted to evaluate the capability of this system in capturing and measuring objects with various levels of opacity. These experiments consist of two important stages, namely the detection of single static objects with three different opacity levels and the detection of two static objects with different opacity levels. The first stage is to confirm the system's ability to capture and analyse these objects. The second stage is to prove that multiple objects can be captured and processed in the same pipeline system.

In the final stage of evaluations, the detection of rising air bubbles that were generated by a syringe and by an air pump was carried out. The purpose of these experiments is to prove that moving air bubbles can be detected by this system. Part of the evaluation is to analyse the air bubble's diameter and velocity with two-plane sensor alignments. With this technique, the air bubble shape and path can be evaluated.

A few research limitations and assumptions should be mentioned here. In this research, light absorption, reflection and reflectance are included in the theoretical calculation, while light's other characteristics are assumed to be negligible. For the data acquisition system (DAQ), NI USB 6210 is capable of capturing 31k samples per second for each port. There is 40 us of data lost because of this DAQ limitation. So it is assumed that 5 continuous pixels will have the same voltage values as the first pixels sampled. For the experiment involving crystal clear water, the pressure level is assumed at atmospheric pressure level, 101.3 kPa.

## 1.5 Research Methodology in Brief

This research constructs an OPT system using a Sony ILX551A CCD and laser diodes class IIIA oriented in an octagonal shape to give a wide coverage area of an acrylic pipeline system. There are two software programs involved in this research: real-time image reconstruction and offline data measurement. Both softwares are developed in LabVIEW. For real-time image reconstruction, Linear Back Projection and filtered algorithms are applied. For offline programming, data on the object diameter and velocity are collected for evaluation. Several experiments are conducted to investigate the capability of this OPT system in detecting and capturing images of static or moving solid and transparent objects. The data collected shall be analysed and evaluated using a statistical engineering analysis technique with the help of Minitab software.

## 1.6 Structure of Thesis

This thesis consists of six chapters as described below.

- i. Chapter 1 briefly describes the research background, problems statements, objectives, scopes, and its contributions.
- ii. Chapter 2 consists of a literature review on tomography systems, light characteristics, OPT image reconstruction, CCD sensors, multiphase flow criteria, bubble characteristics and detectors.
- iii. Chapter 3 discusses the optical system modelling and image reconstruction modelling.
- iv. Chapter 4 presents the research methodology for the OPT hardware development and LabVIEW programming.
- v. Chapter 5 presents the experiments and results for static objects and moving air bubbles. Detailed analysis and discussion on diameter measurement, object velocity and image reconstruction are examined here.
- vi. Chapter 6 is the final chapter with the research conclusions and recommendations for future work.

## REFERENCES

1. Beck, M.S and Williams, R.A. Process Tomography : A European Innovation and Its Applications. *Measurement Science Tecnology*.1996. 7: 215-224
2. Michaelides, E.E. Examples of Applications in Science and Technology. *Particles, Bubbles and Drops: The Motion , Heat and Mass Transfer*. New Orleans. World Scientifc. 17-22: 2007
3. Abdul Rahim, R. *Optical Tomography System: Principles, Technique and Applications*. Malaysia: Universiti Teknologi Malaysia. 2011.
4. Buvat, I., Darcourt, J. and Franken, P. Single Photon Emission Computed Tomography. In: G.Pierre. *Digital Signal and Image Processing: Tomography*. Virginia : John Willey & Sons. 329-350: 2009
5. Abdul Rahim, R. Optical Tomography: Principles, Techniques, and Applications. Johor Bahru. Malaysia: Universiti Teknologi Malaysia, 2011.
6. Ibrahim, S., Yunus, M. A. M., Green, R.G. and Dutton, A.K. Concerntation Measurement of Bubbles in a Water Column Using an Optical Tomography System. *ISA Transactions*. 2012. 51: 821-826.
7. York, T. Status of Electrical Tomography in Industrial Applications. *Journal of Electronic Imaging*. 2001. 10(3) : 606-619
8. Pierre, G. *Digital Signal and Image Processing Tomography*. Virginia: John Wiley & Sons Inc. 2009
9. Beck, M. and William, R. Process Tomography: European Innovation and Applications. *Measurement Science Technology*. 1996. 7: 215-224
10. West, R.M., Jia. X., and Williams, R.A. Parametric Modeling in Industrial Process Tomography. *Chemical Engineering Journal*. 2000. 77:31-36
11. Williams, R.A. Tomographic Imaging for Modeling and Control of Mineral Process. *The Chemical Engineering Journal*. 1995. 59: 71-85

12. Beck, M. S., Dyakowski, T. and William, R. A. Process Tomography –The State of Art. Transducer and Instrumentation. *Transactions of the Institute of Measurement and Control*. 1998. 20(4):163-177
13. Michelsen, C. A Review of Reconstruction Techniques for Capacitance Tomography. *Measurement Science Technology*. 1995. 7:325-337
14. Bennett, M., West, R. M., Luke, S. P. and William, R. A. The Investigation of Bubble Column and Foam Process Using Electrical Capacitance Tomography. *Minerals Engineering*. 2002. 15: 225-234
15. Yang, W. Q. and Liu, S. Role of Tomography in Gas/Solids Flow Measurement. *Flow Measurements and Instrumentation*. 2000. 11: 237-244
16. Xie, C., Renecke, N., Beck, M., Mewes, D. and Williams, R. A. Electrical Tomography Technique for Process Engineering Applications. *The Chemical Engineering Journal*. 1995. 56: 127-133
17. Wang, M., Dickin, F. J. and William, R. A. Electrical Resistance Tomography of Metal Walled Vessels and Pipelines. *Electronics Letters*. 1994. 30:771-773
18. Beck, M. S. and Williams, R.A. Selection of Sensing Techniques. In: *Process Tomography: Principles, Techniques and Applications*. Oxford: Butterworth and Heinemann. 41-48:1995
19. Wang, H. H., Fedchenia, I., Shiskin, S., Finn, A., Smith, L. and Kolket, M. Electrical Capacitance Tomography: A Comprehensive Sensing Approach. *IEEE International Conference*. 2012. 590-594
20. Okonkwo, A. D., Wang, M. and Azzopardi, B. Characterisation of a High Concentration Ionic Bubble Column Using Electrical Resistance Tomography. *Flow Measurement and Instrumentation*. 31: 69-76
21. Kim, S., Lee, E. J., Woo, E. J. and Seo, J. K. Asymtotic Analysis of the Membrane Structure to Sensitivity of Frequency Difference Electrical Impedance Tomography. *Inverse Problem*. 2012. 28(7):075004.
22. Decai, L., Fuqun, S. and Yiangxia, C. Optimum Design of an Internal 8 Electrode Capacitance Tomography Sensor Array. *Advanced Materials Research*. 2012. 508:84-87
23. Daily, W., Ramirez, A., Binley, A. and Labrecque, D. Electrical Resistance

- Tomography. *The Leading Edge*. 2004. 23(5):438-42
24. Jin, H., Wang, M., and Williams, R. A. Analysis of Bubble Behaviours in Bubble Columns Using Electrical Resistance Tomography. *Chemical Engineering Journal*. 2007. 130(2):179-85
  25. Boone, K. and Holder, D. S. Current Approaches to Analogue Instrumentation Design in Electrical Impedance Tomography. *Physiological Measurement*. 1996. 17(4):229
  26. Jordana, J., Gasulla, M. and Areny, R. Electrical Resistance Tomography to Detect Leaks from Buried Pipes. *Measurement Science Technology*. 2001. 12(8):1061
  27. Khana, A. Electrical Impedance Tomography. *ECE 5030 Professor Land*. 1-11.
  28. Wang, H. H., Fedchenia, I., Shiskin, S., Finn, A., Smith, L. and Kolket, M. Image reconstruction for electrical capacitance tomography exploiting sparsity. In *Future of Instrumentation International Workshop (FIIW)*. 2012. 1-4
  29. Barty, A., Kupper, J. and Chapman, H. N. Molecular Imaging Using X-Ray Free Electron Lasers. *Annual Review Physics Chemical*. 2013. 64:415-435
  30. Hawkesworth, M. R. and Parker, D. J. Emission Tomography. In: Beck, M. and William, R. *Process Tomography: Principles, Techniques and Applications*. Oxford: Butterworth and Heinemann. 199-223: 1995
  31. Caumes, J., Younus, A., Salort, S., Chassagne, B., Recur, B., Ziéglé, A., Dautant, A. and Abraham, E. Terahertz tomographic imaging of XVIIIth Dynasty Egyptian sealed pottery. *Applied optics*. 2011. 50(20):3604-3608
  32. Wildenschild, d., Hopmans, J. W., Vaz, C. M. P., Rivers, M. L. and Rikard, A. D. Using X-ray computed tomography in hydrology : systems, resolutions, and limitations. *Journal of Hydrology*. 2002. 267(3):285-297
  33. Dahlbom, M. and Hoffman, E. J. An Evaluation of a Two Dimensional Array Detector for High Resolution PET. *Medical Imaging, IEEE Transactions*. 1998. 7(4):264-72
  34. Kawase, K., Shibuya, T., and Suizu, A. K. THz imaging techniques for nondestructive inspections. *Comptes Rendus Physique*. 2010. 11(7):510-8
  35. Lee, N. and Hyeon, T. Designed Synthesis of Uniformly Sized Iron Oxide



- Nanoparticles for Efficient Magnetic Resonance Imaging Contrast Agents. *The Royal Society of Chemical*. 2012. 41: 2575-2589
36. Muehllehner and Karp, S. Positron emission tomography. *Physics in Medicine and Biology*. 2006. 51(3): 117-137
  37. Ferguson, B., Wang, S., Gray, D., Abbot, D. and Zhang, X.C. T-ray computed tomography. *Optics Letters*. 2002. 27(15):1312-1314
  38. Wildenschild, D., Vaz, C.M.P., Rivers, M.L., Rikard, D. and Christensen, B.S.B. Using X-ray computed tomography in hydrology systems. *Journal of Hydrology*. 2002. 267(3):285-297
  39. Bessou, M., Duday, H., Caumes, J.P., Salort, S., Chassagne, B., Dautant, A., Ziéglé, A. and Abraham, E. Advantage of terahertz radiation versus x-ray to detect hidden organic materials in sealed vessels. *Optics Communications*. 2012. 285(21): 4175-4179
  40. Buffiere, J. Y., Maire, E., Adrien, J., Masse, J.P. and Boller, E. In Situ Experiments with X ray Tomography: an Attractive Tool for Experimental Mechanics. *Experimental Mechanics*. 2010. 50(3):289-305
  41. Chan, W.L., Deibel, J. and Mittleman, D.M. Imaging with terahertz radiation. *Reports on progress in physics*. 2007. 70(8): 1325
  42. Abdul Rahim, R., Pang, J.F. and San Chan, K. Optical tomography sensor configuration using two orthogonal and two rectilinear projection arrays. *Flow Measurement and Instrumentation*. 2005. 16(5):327-340
  43. Schweiger, M., Arridge, S.R. and Delpy, D.T. Application of the finite-element method for the forward and inverse models in optical tomography. *Journal of Mathematical Imaging and Vision*. 1993. 3(3):263-283
  44. Jackson, R. G. The Development of Optical System for Process Imaging. In: Beck, M. and William, R. *Process Tomography: Principles, Techniques and Applications*. Oxford: Butterworth and Heinemann. 1995
  45. Christoph, H. Optical Tomography. *Annual Review of Analytical Chemistry*. 2012.
  46. Davis, G.R., Evershed, A.N. and Mills, D. Quantitative high contrast X-ray microtomography for dental research. *Journal of dentistry*. 2013. 41(5):475-482

47. Semenov, S. Microwave tomography : review of the progress towards clinical applications progress towards clinical applications. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*. 2009. 367(1900):3021-3042
48. Abdul Rahim, R., Green, R.G., Horbury, N., Dickin, F.J., Naylor, B.D. and Pridmore, T.P. Further Development of a Tomographic Imaging System Using Optical Fibres for Pneumatics Conveyers. *Measurement Science Technology*. 1996. 7(3):419
49. Yan, C., Zhong, J., Liao, Y., Lai, S., Zhang, M. and Gao, D. Design of an Applied Optical Fiber Process Tomography System. *Sensors and Actuators B: Chemical*. 2005. 104(2):324-331
50. Yunos, Y.M., Abdul Rahim, R., Muji, S.Z.M., Rahiman, M.H.F. and Puspanathan, M.J. Initial Study on Optical Fiber Array to Produce Particle Size Information for Hydraulic Process. *Technical Note-Electrical Engineering*. 2013. 38(8):2193-2195
51. Yan, C., Liao, Y., Lai, S., Gong, J. and Zhao, Y. A Novel Optical Fibre Process Tomography Structure for Industry Process Control. *Measurement Science Technology*. 2002. 13(12):1898
52. Ramli, N., Green, R.G., Abdul Rahim, R., Evans, K. and Naylor, B. Fibre Optic Lens Modelling for Optical Tomography. *1st World Congress on Industrial Process Tomography*. 1999. 517-521
53. Ibrahim, S., Green, R.G., Dutton, K. and Abdul Rahim, R. Lensed Optical Fiber Sensors for Online Measurement of Flow. *ISA Transaction*. 2002. 41:13-18
54. Abdul Rahim, R., Leong, L.C., Chan, K.S., Pang, J.F. and Rahiman, M.F. Tomographic Imaging: Multiple Fan Beam Projection Technique Using Optical Fiber Sensors. *Optical Engineering*. 2007. 46(4):047004-047004
55. Abdul Rahim, R., Rahiman, M.H.F., Chen, L.L., San, C.K. and Fea, P.J. Hardware Implementation of Multiple Fan Beam Projection Technique in Optical Fibre Process Tomography. *Sensors*. 2008. 8(5):3406-3428
56. Abdul Rahim, R., Fea, P.J., San, C.K. and Rahiman, M.F. Optical Tomography: Infrared Tomography Sensor Configuration Using Four Parallel Beam Projection. *Sensors and Transducers*. 2006. 72(10): 761-768.

57. Gangulay, A. K. Laser. In: *Optical and Optoelectronic Instrumentation*. Asansol, India: Alpha Science International LTD. 7.1-7.32. 2010
58. Abdul Rahim, R. and Chan, K. S. Optical Tomography System for Process Measurement Using Light Emitting Diodes as a Light Source. *Optical Engineering*. 2004. 43(5):1251-1257
59. Prati, F., Guagliumi, G., Mintz, G.S., Costa, M., Regar, E., Akasaka, T., Barlis, P., Tearney, G.J., Jang, I.K., Arbustini, E. and Bezerra, H.G. Expert Review Document Part2: Methodology, Terminology and Clinical Applications of Optical Coherence Tomography for the Assesment of Interventionaal Procedures. *European Heart Journal*. 2012. 33:2513-2522
60. Yunos, M. Y., Mansor, M.S.B., Nor Ayob, N.M., Fea, P.J., Abdul Rahim, R. and San, C.K. Infrared Tomography Sensor Configuration Using Four Parallel Beam Projection. *Sensors and Tranducers*. 2006. 10:761-768
61. Idroas, M. A Charge Coupled Device Based on Optical Tomographic Instrumentation System for Particle Sizing. Ph. D. Thesis. Sheffield Hallam University; 2004.
62. Ramli, N., Idroas, M., Ibrahim, M.N. and Shafei, N.H. Design of the Optical Tomography System for Four Projections CMOS Linear Image. *Jurnal Teknologi*. 2013. 61(2):1-7
63. Abdul Rahim, R. and Green, R.G. Optical Fibre Sensor for Process Tomography. *Control Engineering Practice*. 1998. 6:1365-1371
64. Ibrahim, S., Green, R.G., Dutton, K., Evans, K., Abdul Rahim, R. and Goude, A. Optical Sensor Configuration for Process Tomography. *Measurement Science Technology*. 1999. 10(11):1079
65. Abdul Rahim, R., Rahiman, M.F., Goh, C.L., Muji, S.M., Abdul Rahim, H. and Yunos, Y.M. Modelling Orthogonal and Rectilinear Mixed Modality Projection of Optical Tomography for Solid Particles Concerntation Measurement. *Sensors and Actuators A : Physical*. 2010. 161:53-61
66. Ibrahim, S. and Green, R.G. Optical Tomography for Imaging Process Flow. *Proc. MSTC*. 2001.149-155
67. Abdul Rahim, R., Chen, L.L., San, C.K., Fazalul Rahiman, M.H. and Fea, P.J. Multiple Fan Beam Optical Tomography : Modelling Techniques. *Sensors*.

2009. 9: 8562-8578

68. Muji, S.Z.M., Abdul Rahim, R., Rahiman, M.H.F., Tukiran, Z., Ayob, N.M.N., Mohamad, E.J. and Puspanathan, M.J. Optical Tomography: Image Improvement Using Mixed Projection of Parallel and Fan Beam Modes. *Measurement*. 2013. 46:1970-1978
69. Abdul Rahim, R. A Tomographic Imaging System for Pneumatic Conveyers Using Optical Fibres. Sheffield Hallam University. Ph. D. Thesis; 1996.
70. Ibrahim, S. Measurement of Gas Bubbles in a Vertical Column Water Using Optical Tomography. Sheffield Hallam University. Ph. D. Thesis; 2000.
71. San, K. S. and Abdul Rahim, R. Tomographic Imaging of Pneumatic Conveyer Using Optical Sensor. *Proceedings of 2nd World Engineering Congress*. Kuching, Sarawak, Malaysia. 2002.
72. Muji, S.Z.M., Sari, S., Abdul Rahim, R. and Rahiman, M.H.F. Optical Tomography: A New Filter Technique for Post Processing Image. *IEEE International Conference on Control System, Computing and Engineering*, Penang, Malaysia, 2012. 473-476
73. Arai, T., Yonai, J., Hayashida, T., Ohtake, H., van Kuijk, H. and Etoh, T.G. A 252-V/Lux.s, 16.7 Million Frame per Second 312-kpixel Back Side Illuminated Ultrahigh Speed Charged Coupled Device. *IEEE Transaction on Electron Devices*. 2013. 3450-3458
74. Boyd, J.T. and Chen, C.L. An Integrated Optical Waveguide and Charged Coupled Device Image Array. *Quantum Electronics, IEEE Journal*. 1977. 13(4):282-287
75. Buil, C. Principles and Performance of the CCD. In: *Charged Coupled Device(CCD) Astronomy*, Virginia, Willman Bell Inc.1-2: 1991
76. Kawamoto, S., Watanabe, Y., Otsuka, Y. and Narabu, T. A CCD Colour Linear Image Sensor Employing New Transfer Method. *Consumer Electronics, IEEE Transactions*.1991. 37(3):481-486
77. Etoh, T.G., Poggemann, D., Kreider, G., Mutoh, H., Theuwissen, A.J., Ruckelshausen, A., Kondo, Y., Maruno, H., Takubo, K., Soya, H. and Takehara, K. An Image Sensor which Captures 100 Consecutive Frames at 1000000 frames/ second. *IEEE Transaction on Electron Device*. 2003.

50(1):144-151

78. Buil, C. Principle and Performance of CCD. In: *CCD Astronomy: Construction and Use of an Astronomical CCD Camera*. Virginia: Willmann Bell Inc. 26-28; 1991
79. Buil, C. Transfer Efficiency. *CCD Astronomy: Construction and use of an Astronomical CCD Camera*. Virginia: Willmann Bell Inc. 29-30; 1991
80. Kosman, S.L., Stevens, E.G., Cassidy, J.C., Chang, W.C., Roselle, P., Miller, W.A., Mehra, M., Burkey, B.C., Lee, T.H., Hawkins, G.A. and Khosla, R.P. A Large Area 1.3 Mega Pixel Full Frame CCD Image Sensor with a Lateral Overflow Drain and Transparent Gate Electrode. *Electron Devices Meeting*. 1990. 287-290
81. Felber, P. Charged Coupled Device. *A literature study as a project for ECE*. 2002. 575: 8-9
82. Gao, J., Zhang, Z., Yao, R., Sun, J. and Zhang, Y. A Robust Smear Removal Method for Interframe Charged Coupled Device Star Images. *Natural Computation*. 2011. 3:1805- 1808
83. Buil, C. The Electronics of a CCD Camera. In: *Charged Coupled Device : Astronomy*. Virginia: Willmann Bell Inc. 56-57; 1991
84. Karellas, A., Liu, H., Reinhardt, C., Harris, L.J. and Brill, A.B. Imaging of Radionuclide Emissions with a Low Noise Charged Coupled Device. *Nuclear Science, IEEE Transactions*. 1993. 40(4):979-982
85. Shott, J.D., Melen, R.D. and Meindl, J.D. Charged Coupled Device for use in Electronically Focused Ultrasonic Imaging System. *Communications, Radar and Signal Processing*. 1980. 127(2):144-154
86. Suzuki, N., Yamada, T., Sekins, H. and Goto, H. A CCD Linear Image Sensor. *IEEE International Solid State: Optoelectronic Circuit*. 1982. 127:34-36
87. Tian-ze, Li, F. W., Heng-wei, L. and Li-xiu, M. Study on the Treatment Technology and Application of Charged Coupled Device. *In Image and Signal Processing*. 2009. 1-5
88. Poli, D. Georeferencing ogf Multi Line CCD Array Optical Sensors with a General Photogrammetric Model. *Geoscience and Remote Sensing Symposium*.

2003. 6:3908-3910

89. Idroas, M., Abdul Rahim, R., Green, R.G., Ibrahim, M.N. and Rahiman, M.H.F. Image reconstruction of a charge coupled device based optical tomographic instrumentation system for particle sizing. *Sensors*. 2010. 10(10):9512-9528
90. Muji, S.Z.M., Abdul Rahim, R., Rahiman, M.H.F., Sahlan, S., Shaib, M.F.A., Jaysuman, M. and Mohamad, E.J. Optical tomography: a review on sensor array, projection arrangement and image reconstruction algorithm. *International Journal of Innovative Computing, Information and Control*. 2011. 7(7):1-17
91. Li, Q.P., Ding, F. and Fang, P. Flash CCD Laser Displacement Sensor. *Electronics Letter*. 2006. 42(16): 910-912
92. Hong, Z., Xuan, W. and Rui, W. High Speed on Line Measurement of Digital Wire Outer Diameter with Laser and CCD Technology. *Proceedings of the 7th International Conference on Properties and Applications of Dielectrics Materials*. 2003. 2:812-815
93. Zhou, A., Guo, J. and Shao, W. Automated Detection of Surface Defects on Sphere Parts Using Laser and CCD Measurement. *IECON 2011-37th Annual Conference on IEEE Industrial Electronics Society*. 2011. 2666-2671
94. Ni, Y., Yu-tian, W., Jiang-tao, L. and Huan-huan, L. Research on Thickness Measurement of Transparent Object Based on CCD. *International Conference on Measuring Technology and Mechatronics Automation*. 2009. 1:113-116
95. Fei, Z., Guo, J., Wang, J. and Luo, G. The Application of Laser and CCD Compound Measuring Method on 3D Object Detection. *Proceeding of the International Conference on Mechatronic and Automation*. 2010. 1199-1202
96. Yusri, M. Y., Mansor, Ayob, N. M. N., Fea, P. J., Abdul Rahim, R. and San, C. K. Infrared Tomography Sensor Configuration Using 4 Parallel Beam Projection. *Jurnal Teknologi*. 2012. 55(1):101-111
97. Telling, R.H. and Walton, A.J. Bernoulli excitation and detection of gas bubbles. *Ultrasonics*. 2001. 39: 455-459
98. Zhan, Y., Gu, K., Yang, F., Wu, H. and Yu, M. A Bubble Detection Technique Based on Light Intensity and Mie Scattering Theory for Spinning Solution. *Optik-International Journal for Light and Electron Optics*. 2013. 124(20):4236-4239

99. Michaelides, E. E. *Particles, Bubbles and Drops*, New Orleans. World Scientific. 2007
100. Yang, G.Q., Du, B. and Fan, L.S. A Review- Bubble Formation and Dynamics in Gas, Liquid, and Solid Fluidization. *Chemical Engineering Science*. 2007. 62:2-27, 2007.
101. Levich, V. *Physicochemical Hydrodynamic*, Enlewood Cliff: Prentice Hall, 1962.
102. Amaya, L. and Lee, T. Single Bubble Rising Dynamics for Moderate Reynolds number using Lattice Boltzmann Method. *Computers and Fluids*. 2010. 39: 1191-1207
103. Tomiyama. Reconsideration of Three Fundamental Problems in Modelling Bubbly Flows. *European Two Phase Flow Group Meeting*. Portugal. 2001
104. Amans, J. L. and Feretti, G. Computed Tomography. In: Pierre, G. *Digital Signal and Image Processing Series: Tomography*. London: John Wiley & Sons Inc. 259-285; 2009
105. Gang, L., Hong-bin, S., Li, L., Chu, Z., Shao-juan, M. and Yuan-bo, W. Laser Induced Damages to Charge Coupled Device Detector Using a High Repetition Rate and High Peak Power Laser. *Optics and Lasers Technology*. 2012. 47:221-227
106. Shen, H., Ran, M., Hu, J. and Yao, Z. An Experimental Investigation of Underwater Pulsed Laser Forming. *Optics and Lasers in Engineering*. 2014. 62:1-8
107. Choudhury, A. K. R. Object Appearance and Colour. In: *Principles of Colour and Appearance Measurement: Object Appearance, Colour Perception and Instrumental Measurement*. Woodhead Publishing Limited, 64-69; 2014
108. Ganguly, A. K. Dispersion. In: *Optical and Optoelectronic Instrumentation*. Anasol: Alpha Science International LTD. 5.1-5.19; 2010
109. Dugdale, W. An Optical Instrumentation System for the Imaging of Two Component Flow, United Kingdom: University of Manchester, Ph. D. Thesis. 1994.
110. Ganguly, A. K. Geometrical Optics. In: *Optical and Optoelectronic*

- Instrumentation*. Anasol, India: Alpha Science International LTD. 2.1-2.17; 2010
111. Ibrahim, S. and Green, R.G. Velocity measurement using optical sensors. *Semiconductor Electronics Proceedings. ICSE 2002. IEEE International Conference.2002.* 126-129
112. Muji, S.Z.M., Goh, C.L., Ayob, N.M.N., Abdul Rahim, R., Rahiman, M.H.F., Abdul Rahim, H., Pusppanathan, M.J. and Fadzil, N.S.M. Optical tomography hardware development for solid gas measurement using mixed projection. *Flow Measurement and Instrumentation*. 2013. 33:110-121
113. Huang, S. and Xie, C. Error Analysis. In: Beck, M. and William, R. *Process Tomography: Principles, Techniques and Applications*, Butterworth-Heinemann, 2012.
114. Grass, M., Guillemaud, R. and Rasche, V. Interventional X-Ray Volume Tomography. In : Pierre, G. *Digital Signal and Image Processing : Tomography*. Virginia: John Wiley & Sons. 287-306; 2009
115. Thomas, A., Barton, R. and Chuke-Okafor, C. Applying lean six sigma in a small engineering company-a model for change. *Journal of Manufacturing Technology Management*. 2008. 20(1):113-129
116. Ross, M. S. Test Concerning the Mean of a Normal Population. In: *Probability and Statistics for Engineers and Scientist*. Burlington, USA: Elsevier Academic Press. 3027-313; 2009
117. Vrij. Possible Mechanism for the Spantaneous Rupture of Thin, Free Liquid Film. *Discussion of the Faraday Society*. 1966. 42:23-33
118. Luo, X., Lee, D.J., Lau, R., Yang, G. and Fan, L.S. Maximum Stable Bubbles Size and Gas Hold Up in High Pressure Slurry Bubbles Column. *A.J.Chemical Engineering*. 1999. 45:665-680