

EMBEDDED INSTRUMENTATION SYSTEM FOR OPTICAL TOMOGRAPHY
BASED ON IMAGE SENSORS

MOHD AMIR HAMZAH BIN AB GHANI

UNIVERSITI TEKNOLOGI MALAYSIA

EMBEDDED INSTRUMENTATION SYSTEM FOR OPTICAL TOMOGRAPHY
BASED ON IMAGE SENSOR

MOHD AMIR HAMZAH BIN AB. GHANI

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*To my beloved family, friends
and lecturers who have guided
and inspired me along the journey.*

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ABSTRACT

Tomography technique was used widely for its visualisation by section ability. The technique that is popularly used in process industry has high efficiency and is able to improve manufacturing sector. Optical tomography can capture images of objects moving in high speed is a convenience and commonly used in process industry particularly in chemical process. Optical tomography system can be embedded with a controlling unit capable of giving instructions in which to operate the optical sensors. The embedded controlling unit helps reduce processing time of data collection and can be conveniently placed in a minimal working space environment. The main component for the embedded optical tomographic system is the Charge Coupled Device (CCD) used as an image sensor. The SONY ILX551A CCD sensor that has 2048 effective pixels was placed outside of a pipe on an octagon shape Perspex due to its non-intrusive nature. There are four projections used for the tomography system with a single CCD sensor placed at each end of the projection. The CCD sensors are controlled by an embedded system including an ATMEGA1284P microcontroller that produces driving signals needed to turn on the four CCDs in the system. The microcontroller Timer function generates the signal according to the sequence needed by the CCD sensors. The speed of the data produced correlates with the speed of the timing signals sent out from the microcontroller. The experimental result recorded was based on the four conditions: when the sensors were fully open, fully closed, half open and when an object is present. The image of when an object present condition was produced through image processing method. Hence, the embedded instrumentation system for optical tomography based on image sensors manages to obtain data accordingly to the sensors detection.

ABSTRAK

Teknik tomografi telah digunakan secara meluas kerana kemampuannya untuk visualisasi secara seksyen. Teknik yang digunakan oleh pemaju dalam industri pemprosesan mempunyai kecekapan yang tinggi dan mampu meningkatkan sektor pembuatan. Tomografi optik dapat menangkap gambar objek yang bergerak dalam kelajuan yang tinggi dengan mudah dan banyak digunakan dalam industri pemprosesan terutama dalam bidang proses kimia. Sistem tomografi optik boleh diasimilasikan dengan unit pengendali yang mampu memberi arahan untuk mengoperasikan sensor optik. Unit kawalan tertanam membantu mengurangkan masa pemprosesan pengumpulan data dan boleh dipasang dengan mudah di dalam persekitaran ruang kerja yang minimum. Komponen utama sistem tomografi optik yang tertanam adalah Peranti Ditambah Caj (CCD) yang digunakan sebagai penerima imej. SONY ILX551A penerima CCD yang mempunyai 2048 piksel berkesan ditempatkan di luar paip yang berbentuk oktagon Perspex oleh kerana sifat non-intrusif. Ada empat unjuran yang digunakan untuk sistem tomografi dengan satu penerima CCD diletakkan di setiap hujung unjuran. Penerima CCD dikendalikan oleh sistem terbenam termasuk pengawal mikro ATMEGA1284P yang menghasilkan isyarat memandu diperlukan untuk menghidupkan empat CCD dalam sistem. Fungsi pemasa pada mikropengawal menjana isyarat mengikut turutan yang diperlukan oleh penerima CCD. Kelajuan data yang dihasilkan bergantung kepada kelajuan isyarat masa yang dihantar keluar dari pengawal mikro. Hasil eksperimen dicatatkan adalah berdasarkan empat syarat: apabila sensor terbuka sepenuhnya, ditutup sepenuhnya, separuh terbuka dan ketika objek hadir. Imej apabila keadaan objek yang hadir telah dihasilkan melalui kaedah pemprosesan imej. Oleh itu, sistem instrumentasi yang tertanam untuk tomografi optik berdasarkan penerima imej mampu mendapatkan data yang dikehendaki untuk pengesanan penerima.

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LIST OF ABBREVIATIONS

CLK	-	Clock Signal
CCD	-	Charge-coupled Device
DAQ	-	Data Acquisition System
DAS	-	Data Acquisition System
DC	-	Direct Current
EEPROM	-	Electrical Erasable Programmable Read-Only Memory
ECT	-	Electrical Capacitance Tomography
LED	-	Light Emitting Diode
MCU	-	MicroController Unit
MPU	-	MicroProcessor Unit
OFPT	-	Optical Fibre Process Tomography
P1	-	Projection One
P2	-	Projection Two
P3	-	Projection Three
P4	-	Projection Four
PC	-	Personal Computer
PIC	-	Peripheral Interface Controller
PWM	-	Pulse Width Modulation
ROG	-	Read Out Gate

LIST OF SYMBOLS

α	-	linear coefficient
cm	-	centimeter
f_0	-	Focal length
I	-	Current
I	-	Intensity
kHz	-	kiloHertz
ln	-	natural log
m	-	meter
mA	-	milliampere
mm	-	millimeter
MHz	-	megaHertz
n_t	-	transmitted refractive index
n_i	-	incidence refractive index
R	-	Resistor
V	-	Voltage

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The word tomography was derived from word tomos which means volume in Greek and graphein which means to write. It is also described as the idea of ‘a section’ or ‘a slice’. Therefore tomography is imaging by sections or in other word, sectioning. The method is well known and widely used in archaeology, biology, radiology, geophysics and other sciences. Tomography is also an important techniques used even in the nuclear fields (Itami *et al*, 2001).

Several techniques or methods have been discovered and reinvented in the field of industrial process tomography. Each technique has its own advantages and limitations and it is difficult to select the most practical application as each technique is unique in its own way. With the right combination of application, it could provide good productivity and quality result. (Bogolubov *et al*, 2005; Zeni *et al*, 2000).

It is largely used in manufacturing science and material processing for its non-contact properties and it helps reduce measurement error (Xu *et al*, 2011; Zeng *et al*, 2010; Luo *et al*, 2008; Wang *et al*, 2014). The technique is capable resolving the measurement precision problem (Zhao *et al*, 2013a; Zhao *et al*, 2013b; Zhao *et al*, 2012b) and popularly used in biomedical imaging system (Chang *et al*, 2013; Chaudhari *et al*, 2005). The optical system in biomedical aim to increase acquisition speed and be non-intrusive (Stifter *et al*, 2008; Bezerra *et al*, 2009). The application of tomography in biomedical can even imaging the blood vessel (Ko *et al*, 2005).

The tomography method was also used in army industry science and air flight (Han *et al*, 2014). For process industry especially in chemical process, optical tomography has been used in many latest equipment with optical fibre being one of it (Ramli *et al*, 1999). Various tools or system are being produced at all time to improve the measurement process. It becomes important as optical tomographic image can help to capture image that are hard to see with our bare eyes, thus improving productivity and reducing wastage. The benefits are useful to everyone involved in the process industry.

The system of optical tomographic instrumentation based on the charge-coupled device (CCD) linear image sensor has the ability to fully measure the cross section of the pipe. In addition, the optical tomographic system is known as safe and non-intrusive (Zhang *et al*, 2008). The optical tomography is also useful for investigating and monitoring flow of solid or gas (Mohd Zain *et al*, 2010). Direct contact of the transducer and the measurand are not necessary. The efficiency of the technique is high and has the possibility to improve manufacturing sector especially in the chemical industries. The technique is also able to provide measurements via on-line.

1.2 Project Background

In order to get a better understanding of some chemical process, an approach that is more subtle is required. Process tomography is a medium used as a visualizer to look into the interior section of industrial processes. The images of tomography will give valuable information of the process. It will give insight knowledge that is good and beneficial for on-line monitoring and equipment designs. (Peyton *et al*, 1996; Wang *et al*, 1999).

Current work in finding new investigative techniques has given more attention on the use of tomography to three-dimensional and cross-sectional images of internal multi-phase flow behaviour process flow (Simon *et al*, 1994). The

tomographic system mostly composes of an array of sensors, a signal conditioning system, data acquisition system, and a display system (Green *et al*, 1998). Whereby, the collected data are processed by using an algorithm that will reconstruct it and produce images (Xie *et al*, 1989).

Optical approach is by nature non-intrusive and considered as safe due to the fact that the transducer does not need direct physical contact with the measurand. The technique known to has high efficiency (Kostov *et al*, 2000) and could enhance manufacturing especially in the chemical industries (Leutwyler *et al*, 1994). For processes that handle transparent fluids and where optical access is possible, this technique can offer images in high-resolution state (Beck *et al*, 1995). The optical tomography technique also capable of performing on-line measurements due to its direct optical characteristic (Black et al, 1996).

1.3 Problem Statement

Various tools and methods for optical tomography had been done especially in process industry. The methods used are being improved from time to time in order to optimize the efficiency and accuracy of the system.

Any tomography system contains few limitations that can be overcome or improved in the future work. The technology is always expanding and improving as we know it. Often a microcontroller is used in the system to control the flow of the process and data transfer. An improved and fast microcontroller can be used to obtain an efficient result and fast, regardless of what type of microcontroller used, especially in the data acquisition process. Faster PC is available now rather than in previous project to cut short processing time (Mariani, 2004).

1.4 Research Objectives

1. To design and to develop an embedded tomographic instrumentation system that is based on charge-coupled device (or better known as CCD) linear image sensor.
2. To evaluate performance of the developed system in terms of capabilities and adaptabilities of the microcontroller used to handle the image sensors.

1.5 Research Scope and Limitation

In order to achieve the objectives of this project, the scope of the project are:-

- i Study the programmable microcontroller used for the system which is ATMEL ATMEGA1284P microcontroller, a high performance, low power 8 bit microcontroller.
- ii Generate driving signals based on ATMEL ATMEGA1284P microcontroller to activate the CCD Sony ILX 551A a linear image sensor, which is capable of capturing an image of 2048 pixels.
- iii Develop timing signals to acquire and to capture CCD raw data using ATMEGA on-chip Timer.
- iv Develop a complete embedded instrumentation system for four-projection optical tomography system that is suitable for solid in air environment.

1.6 Organization of the Thesis

Chapter 1 of this thesis explains the background of process tomography. The background of the project, problem statement, objectives and the scopes of the project are defined. The development of the project is based on the subject discussed in this chapter as well as introduction to tomography. Chapter 2 discusses the previous works and researches done on tomography field with emphasize on embedded system used. Many types of different sensors and control system used in optical tomography are highlighted. Chapter 3 describes the mathematical modelling models of the system based on three types of models – measurement section, light source and particle. Through modelling, the size is calculated and the whole system functionality takes shape. Chapter 4 describes the overall set up of the system, testing tools, lighting system used, the CCD testing, microcontroller system. Step by step process was discussed from software development of the controller board, CCD driver board to hardware testing. Chapter 5 describes in details the output result of the embedded system from four projections in four different types of condition. Chapter 6 discussed the conclusion of the project and recommendation for future works.

REFERENCE

- Abdul Rahim, R., and Chan, K. S., (2004) Optical Tomography System For Process Measurement Using Light-Emitting Diode as a Light Source. *Optical Engineering*. Volume 43(5), 1251-1257.
- Abdul Rahim, R., Chan, K. S., Pang, J. F., and Leong, L. C. (2005a) A Hardware Development for Optical Tomography System Using Switch Mode Fan Beam Projection. *Sensors and Actuators A*. Volume 120, 277-290
- Abdul Rahim, R., Loon, G. C., and San, C. K. (2005b). Ethernet Based Optical Tomography System. *Jurnal Teknologi*. 42(D), 55-64.
- Abdul Rahim, R., Rahiman, M. H. F., Chen, L. L., San, C. K., and Fea, P. Hardware Implementation of Multiple Fan Beam Projection Tec Optical Fibre Process Tomography. *Sensors 2008*. Volume 8, 3406-3428.
- Abdul Rahim, R., Thiam, C. K., and Rahiman, M. H. F. (2008a). An Optical Tomography System Using a Digital Signal Processor. *Sensors*. Vol.8, 2082-2103.
- Akiba, M., Chan, K. P., and Tanno, N. (2003). Full-field optical coherence tomography by two-dimensional heterodyne detection with a pair of CCD cameras. *Optics Letters*. 28(10), 816–818.
- Akiba, M., Chan, K. P., Tanno, N. (2002). Influence of Phase Drift on Optical Coherence Tomography Using a CCD Camera-Based Heterodyne Detection Technique. *Optical Review* 9(4), 170–175.
- Atmel, *Atmel ATMega32 microcontroller datasheet*, Atmel Corporation, 2011.
- Bammes, B. E., Rochat, R. H., Jakana, J., and Chiu, W. (2011) Practical Performance Evaluation Of A 10k x 10k CCD For Electron Cryo-Microscopy. *Journal of Structural Biology*. 175 (2011), 384–393.
- Beck, M. S. and Williams, R. A. (1995). Sensor design and selection. In Scott DM and Williams RA (editors), *Frontiers in Industrial Process Tomography*. New York.

- Bezerra, H. G., Costa, M. A., Guagliumi, G., Rollins, A. M., and Simon, D. I. (2009) Intracoronary Optical Coherence Tomography: A Comprehensive Review: Clinical and Research Applications. *J. A. C. C. Cardiovascular. Interventions*. 11 November 2009 Volume 2, 1035-1046.
- Black, D. L., McQuay, M. Q., and Bonin, M. P. (1996). Laser-based techniques for particle-size measurement: A review of sizing methods and their industrial applications. *Prog. Energy Combust. Sci.* Vol 22, pp 267-306.
- Bogolubov, E., Bugaenko, O., Kuzin, S., Mikerov, V., Monitch, E., Monitich, A., and Pertsov A. (2005) CCD Detectors For Fast Neutron Radiography And Tomography With Cone Beam. *Nuclear Instrument and Methods in Physics Research A* 542 (2005), 187-191.
- Booth, C. R., Jakana, J., and Chiu, W. (2006) Assessing the Capabilities of A 4kx4k CCD Camera For Electron Cryo-Microscopy At 300kv. *Journal of Structural Biology*. 156 (2006), 556–563.
- Booth, C. R., Jiang, W., Baker, M. L., Zhou, Z. H., Ludtke, S. J., and Chiu, W. (2004) A 9A Single Particle Reconstruction From CCD Captured Images On A 200 Kv Electron Cryomicroscope. *Journal of Structural Biology*. 147(2004), 116–127.
- Cao, Z., and Yang, X. C. (2009). Measurement of Temperature Field in Laser Molten Pool by CCD Based on DSP. *Key Engineering Materials*, 392-394, 693–696.
- Chadwick, J. W., Prentice, R. N., Major, P. W., and Lam, E. W. N. (2009) Image distortion and magnification of 3 digital CCD cephalometric systems. *Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology and Endodontolog.*, 107(1), 105–112.
- Chang, Y. J., Tseng, H. L., Chen, C. H., Tan, S. Y., Hsieh, B. T., Chang, W. L., and Huang, W. T. (2013). Development of a CCD-Based Optical Computed Tomography Scanner Used in 3D Gel Dosimetry. *Applied Mechanics and Materials*. Vols.300-301, 1632–1635.
- Chaudhari, A. J., Darvas, F., Bading, J. R., Moats, R. A., Conti, P. S., Smith, D. J., Cherry, S. R., and Leahy, R. M. (2005) Hyperspectral And Multispectral Bioluminescence Optical Tomography For Small Animal Imaging. *Physic. In Medical and. Biology*. 50 (2005), 5421–5441.
- Corlu, A., Choe, R., Durduran, T., Rosen, M. A., Schweiger, M., Arridge, S. R., Schnalf, M. D., and Yodh, A. G. (2007). Three-dimensional in vivo

- fluorescence diffuse optical tomography of breast cancer in humans. *Optics Express*. 15(11), 1128–1139.
- Feng, X. F., Zhang, Q., and Liao, Y. J. (2013). Precision Parts Parallelism Error on-Line Detection Based on the CCD Imaging System. *Applied Mechanics and Materials*. Vols.273, 599–603.
- Fischer, J., and Vcelak, J. (2002b). Position Measurement Using CCD Based Optoelectronic Gate. *12th IMEKO TC 4 International Symposium Electrical Measurement and Instrumentation*, 25-27 September, Zagreb, Croatia.
- Fischer, J., Haasz, V., and Radil, T. (2002a). Simple Device For Small Dimension Measurement Using CCD Sensor. *12th IMEKO TC 4 International Symposium Electrical Measurement and Instrumentation*, 25-27 September, Zagreb, Croatia.
- French, M. J., Waltham, N. R., Newton, G. M., and Wade, R. (1998). A Single Chip CCD Waveform Generator and Sequencer. *SPIE Conference on Optical Astronomical Instrumentation*. March 1998, Kona, Hawaii Vol.3355, 547-559.
- Gao, Y., and Zhang, G. Y. (2013). High Precision Machine Vision System for Outer Diameter Inspection Bearing. *Key Engineering Materials*, 552, 313–318.
- Goldstein, S. R., Daube-Witherspoon, M. E., Green, M. V, and Eidsath, A. (1997). A Head Motion Measurement System Suitable For Emission Computed Tomography. *IEEE Transactions on Medical Imaging*, 16(1), 17–27.
- Green, R. G., Thorn, R. (1998). Sensor system for lightly loaded pneumatic conveyor. *Powder Technology*. Vol 95, pp 79-92.
- Guo, H., Bai, L., Liu, J., and Shi, Y. (2009) Effect of Focusing Status on Dimension Measurement Accuracy in Micro Measurement System Based on CCD. *Key Engineering Materials*, 392-394, 435–438.
- Han, W., Xie, J., Bao, J. H., Zhao, M., Fan, X. Y., and Guo, F. (2014). Application and Analysis of the Full-Wave Band CCD System in Image Interpretation Technology. *Advanced Materials Research*, 989-994, 3782–3785.
- Hongli, S., and Jia, F. (2012) Design of Linear CCD Driving Circuit Based on SCM. *Procedia Engineering* 29 (2012), 3841-3845.
- Huang, W. T., Hung, C. N., Yu, Y. M., Wu, Q. H., and Tuan, C. C. (2013). Exquisite Design of a CCD Analog Front End Module. *Applied Mechanics and Materials*. Vols.300-301, 414–418.

- Ibrahim, S., Green, R. G., Dutton, K., and Abdul Rahim, R. (2002) Lensed optical fiber sensors for on-line measurement of flow. *ISA Transactions*, Volume 41 (2002), 13-18.
- Idroas, M., Abdul Rahim, R., and Green, R. G. (2010b). Image Reconstruction of a Charge Coupled Device Based Optical Tomographic Instrumentation System for Particle Sizing. *Sensors*. Issue 10, 9512-9528.
- Idroas, M., Abdul Rahim, R., Fazalul Rahiman, M. H., Green, R. G., and Ibrahim, M. N. (2010a) Optical Tomography System: Charge-coupled Device Linear Image Sensors. *Sensors & Transducers Journal*, Vol. 120, Issue 9, September 2010a, 62-69.
- Itami, K., Coad, P., Fundamenski, W., Ingesson, C., Lingertat, J., Matthews, G. F., and Tabasso, A. (2001) Observation Of Detachment In The JET MkIIgb Divertor Using CCD Camera Tomography.
- Janesick, J. R (2000). Scientific Charge-coupled Devices. Technical Specification.
- Jiang, B., Li, X., Chen, X., Zhang, T., Feng, C., and Zhang, F. (2012). Technology of Sand Level Detection Based on CCD Images. *Physics Procedia*, 25, 1823–1828.
- Kibrick, R. I., Wright, C., Allen, S. L., and Clarke, D. A. (2004). Optimization of SDSU-2 CCD controller hardware and software for CCD mosaics, *Proceedings of SPIE*. Vol.5496, 178–189.
- Ko, W. S., Kwak, Y. K., and Kim, S. H. (2005) Development Of A Non-Contact Diffuse Optical Tomography System For Image Reconstruction Of Blood Vessel With NIR Light. *IFMBE Proceedings*. Vol. 14/2, 1345-1348.
- Kostov, Y. and Rao, G. (2000). Low-cost optical instrumentation for biomedical measurements. *Review of Sci. Instruments*. Vol 71, 4361-4371.
- Kotov, I. V., Frank, J., Kotov, A. I., Kubanek, P., O'Connor, P., Prouza, M., Radeka, V., and Takacs, P. (2012) CCD Characterization and Measurements Automation. *Nuclear Instruments and Methods in Physics Research*. A 695 (2012), 188–192.
- Leutwyler, K. (1994). Optical Tomography. *Scientific American*. 147-9.
- Li, F. B., Li, Q., and Li, Z. K. (2011). Research on the Transverse Displacement Sensors Using Linear Array CCD. *Advanced Materials Research*. Vols.317-319, 988–991.

- Li, L., and Yang, X. C. (2009). Digital Image Processing of CCD Measuring Temperature Field in Coaxial Powder Stream of Laser Cladding. *Key Engineering Materials*, 392-394, 1037–1041.
- Li, L., Zhang, N., Li, T., Pan, Y., and Dai, Y. (2014). Design Of Area Array CCD Image Acquisition And Display System Based On FPGA, *Proceeding. of SPIE 9284*, 928416-1-928416-10.
- Li, X. M., Yu, A. B., and Ma, L. J. (2012). Study of Shells Exterior Surface Flaw Based on CCD Automatic Detection System. *Applied Mechanics and Materials*. Vols. 201-202, 598–601.
- Lim, H. K. S., and Yang, W. Q. (1999). A Microcontroller-based High-Speed Serial Link For Process Tomography Systems. *1st World Congress on Industrial Process Tomography*. 14-17 April, Buxton, Great Manchester, 377-382.
- Lu, H., Tan, L. Y., Lei, B., Jian, L. S., Wang, Y., Du, F. D., and He, Q. (2010). A Kind of Linear Array CCD Drive Frequency Regulation Technology. *Advanced Materials Research*. Vols.139-141, 2279–2282.
- Luo, Y. M., and Hu, D. J. (2008). On-Line Error Measurement Based On CCD In Quick-Point Grinding Of Curve Parts. *Applied Mechanics and Materials*, Vols. 10-12, 812–816.
- Lytaev, P., Hipp, A., Lottermoser, L., Herzen, J., Greving, I., Khokhriakov, I., ... and Beckmann, F. (2014). Characterization Of The CCD And CMOS Cameras For Grating-Based Phase-Contrast Tomography, *Proceeding. of SPIE 9212*. 921218-921218-10.
- Ma, X., Han, J. L., and Liu, C. S. (2012). Research on CCD Infrared Image Threshold Segmentation. *Applied Mechanics and Materials*. Vols.220-223, 1292–1297.
- Mariani binti Idroas. (2004). A Charge Coupled Device Based Optical Tomographic Instrumentation System for Particle Sizing. Doctor Philosophy, Sheffield Hallam University, United Kingdom.
- Mohamad, E. J., Abdul Rahim, R., Ibrahim, S., Sulaiman, S., and Manaf, M. S. (2006). Flame Imaging Using Laser-Based Transmission Tomography. *Sensors and Actuators*. Volume 127 (A), 332-339.
- Mohd Zain, R., Abdul Rahim, R., Fazalul Rahiman, M. H., and Abdullah, J. (2010). Simulation of Image Fusion of Dual Modality (Electrical Capacitance and

- Optical Tomography) in Solid/Gas Flow. *Sensing and Imaging: An International Journal*. 11(2), 33–50.
- Monoï, M., Sasaki, S., Dobashi, K., Iwai, J., Sekine, H., Tomita, K., Ooki, M., Mashiko, S., Saitou, H., and Itabashi, Y. (2009) A Single Layer CCD Image Sensor with Wide Gap Electrode and Gradual Potential Channel. *SPIE Vol. 7249*. 72490I-1 - 7490I-9
- Monoï, M., Sasaki, S., Nakano, Y., Tsuruta, H., and Yoshida, T. (2005). Low-Capacitance CCD Image Sensor With Thin Single-Layer Structure. *Proceeding. of SPIE-IS&T Electronic Imaging*. Volume 5677, 169–176.
- Nor, I. M. (2013). *CCD Area Image Sensor*. [Technical Drawing]. Duraza Sdn. Bhd.: Senai, Johor.
- Peterson, C. (2010). How it works: The charged-coupled device or CCD. *Journal of young investigators*. Available at: <http://www.jyi.org/volumes/volume3/issue1/features/peterson.html>. Accessed June.
- Peyton, A. J., Yu, Z. Z., and Al-Zeibak, S. (1996). An overview of electromagnetic inductance tomography: description of three different systems. *Meas. Sci. Technol.* Vol 7.
- Piao, D., Jiang, S., Dehghani, H., Srinivasan, S., and Pogue, B. W. (2006). Instrumentation Of Rapid Near-Infrared Diffuse Optical Tomography For Imaging Of Tissue At 35 Frames Per Second. *Proceeding. of SPIE Vol. 6081*. 60810N-1-60810N-9.
- Pöschinger, T., Janunts, E., Brünner, H., and Langenbucher, A. (2010) CCD-based projectional imaging of fluorescent probes in tissue-like media: experimental setup and characterization. *Zeitschrift Fur Medizinische Physik*. 20(4), 299–308.
- Quan, G., Quan, G., Wang, K., Yang, X., Deng, Y., Luo, Q., and Gong, H. (2014). Micro-computed tomography-guided non-equal voxel Monte Carlo method for reconstruction of fluorescence molecular tomography. *Journal of Biomedical Optics*. 17(8), 086006-1-086006-9.
- Ramli, N., Green, R. G., Abdul Rahim, R., Evans, K., and Naylor, B. (1999). Fibre Optic Lens Modelling for Optical Tomography. *1st World Congress on Industrial Process Tomography*. April 14-17 1999, Buxton, Greater Manchester, 517–521.

- Ramli, N., Idroas, M., Ibrahim, M. N., and Shafei, N. H. (2013). Design of the Optical Tomography System for Four Projections CMOS Linear Image Sensor, *Jurnal Teknologi (Sciences & Engineering)*. 61:2, 79–85.
- Salam, Z., and Mohammad Salim, K. (2007). Generation of pulse width modulation (pwm) signals for three- phase inverter using a single- chip microcontroller. *Jurnal Teknologi*. 34(D), 1–12.
- Schulz, R. B., Echner, G., Ruhle, H., Stroh, W., Vierling, J., Vogt, T., Peter, J., and Semmler, W. (2005). Development of a Fully Rotational Non-Contact Fluorescence Tomographer for Small Animals.. 2005 *IEEE Nuclear Science Symposium Conference Record*. 11 November. Germany, 2391-2393.
- Shao, D. X., Li, J., Lin, R., and Wang, G. L. (2011). The Image Process Technology of Micro-Detection for Jet-Pan Based on CCD. *Advanced Materials Research*. Volume 305, 31–36.
- Simon, S. J. R.. (1994). Imaging techniques for fluidised bed systems: a review. In Beck MS et al (editors), *Process tomography: A strategy for industrial exploitation*.
- SONY, *SONY ILX 551A 2048-pixel CCD Linear Sensor (B/W) Datasheet*, Sony Corporation, 2010
- Stefanov, K. D. (2005) CCD-based vertex detector for GLC. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 549(1-3), 87–92.
- Stifter, D., Wiesauer, K., Wurm, M., Leiss, E., Pircher, M., Götzinger, E., Baumann, B., And Hitzenger, C. K. (2008) Advanced Optical Coherence Tomography Techniques: Novel And Fast Imaging Tools For Non-Destructive Testing. *17th World Conference on Nondestructive Testing*, 25-28 Oct 2008, Shanghai, China.
- Tang, T, Huang, Y., Fu, C., and Liu, S. (2009) Acceleration Feedback Of A CCD-Based Tracking Loop For Fast Steering Mirror. *Optical Engineering* January 2009/Volume 48(1), 013001-1 -013001-6.
- Thomas, T. H. M., Devakumar, D., and Ravindran, P. B. (2007). Three-Dimensional Image Reconstruction For CCD Camera Based Optical Computed Tomography Scanner. *2007 IEEE Nuclear Science Symposium Conference Record*. 2965–2967.

- Tian, X. J., Dong, H. J., Li, D. M., and Zhang, X. B. (2012). The Measurement of Small Cylindrical Pieces Based on Digital Image Processing. *Applied Mechanics and Materials*. Vols. 229-231, 1304–1307.
- Tsung, L., Mollon, B., Jia, Y., Mooney, P., Mao, C., and Pan, M. (2008). Development of Fast CCD Cameras for in-situ Electron Microscopy. *Microscopy and Microanalysis*. 14(S2), 808–809.
- Umetsu, E., Akiba, M., Chan, K. P., and Tanno, N. (2003). Non-Scanning Optical Coherence Tomography by an Angular Dispersion Imaging Method. *Japanese Journal of Applied Physics*, 42(Part 2, No. 10B), L1285–L1287.
- Walusiak, S., Podlesny, M., and Pietrzyk, W. (2006) Microprocessor Model to Control ZI Motors. *TEKA Kom. Mot. Energ. Roln.* 6A, 199-206
- Wang, F., Yang, Z. W., Kong, D. R., and Jia, Y. F. (2013a). Research on the High-Speed Object Shadowgraph Image Processing Method Based on Adaptive Threshold Segmentation. *Applied Mechanics and Materials*. Vols. 325-326, 1571–1575.
- Wang, J., and Mei, A. (1999). Industrial monitoring and controlling system of integrated single chip computer with linear CCD image sensor, *SPIE Conference on Process Control and Sensors for Manufacturing*. March 1999. Newport Beach, California. 3589(March), 84–92.
- Wang, W., and Wang, Z. B. (2012a). A Technical Research of Glass Thickness Detection Based on CCD Displacement Sensor. *Applied Mechanics and Materials*, Vols.229-231, 1280–1283.
- Wang, Y. M., Li, Y. M., and Hu, W. Y. (2014). Analysis of Fabric Shape Style Evaluation Method. *Advanced Materials Research*, 1048, 173–177.
- Wang, Y. Q. (2013b). Design of the Intelligent Vehicle System Based on CCD Camera. *Applied Mechanics and Materials*. Volume 274, 278–281.
- Wang, Y., Yan, C. X., and Gao, Z. L. (2012b). Angle Measurements with Laser. *Applied Mechanics and Materials*. Vols.239-240, 206–213.
- Wang, Z. R., Tang, W. Y., and Zhao, X. M. (2013c). Research on Halftone Information Embedding and Extracting Technology Based on CCD Detection. *Applied Mechanics and Materials*. Volume 469, 231–235.
- Wright, C., Kibrick, R., Alcott, B., Gilmore, D. K., Pfister, T., and Cowley, D. (2003). The CCD imaging systems for DEIMOS. *Proceedings of SPIE*. Vol. 4841, 214–229.

- Wu, Y. X., Shi, S. H., Yu, J. L., Yu, L. L., and Wu, J. J. (2012). The Development of Temperature Measurement System in Laser Molten Pool Based on Monochrome CCD with High Speed. *Advanced Materials Research*. Volume 566, 431–434.
- Xie, C. G., Plaskowski, A. J. and Beck, M. S. (1989). Eighth electrode capacitance system for two component flow identification. *IEE Proceeding A*. Vol. 136, 173.
- Xu, G. S. (2013). Method for CCD Edge Signal Processing. *Applied Mechanics and Material*. Volume 441, 695–698.
- Xu, Q., Mei, S. Q., and Zhang, Z. M. (2011). Measurement Method of Yarn Tension Based on CCD Technology. *Advanced Materials Research*. Vols.230-232, 89–93.
- Yang, B., Wang, Y. C., Li, P. H., and Liu, J. L. (2011). HDR CCD Image Sensor System Through Double-A/D Convertors. *Applied Mechanics and Materials*. Vols. 66-68, 2241–2247.
- Yang, P. Y., and Du, Y. (2013). A Fire Monitor Terminal for Reliable and Stable Image Acquisition Based on ARM. *Advanced Materials Research*, 760-762, 1302–1305.
- Zeng, Z., Zhang, J. Q., and Liu, Y. (2010). Surface Temperature Monitoring of Casting Strand Based on CCD Image. *Advanced Materials Research*. Vols. 154-155, 235–238.
- Zeni, L., Bernini, R., and Pierri, R. (2000). Optical tomography for dielectric profiling in processing electronic materials. *Chemical Engineering Journal*, 77(1-2), 137–142.
- Zhang, H., Xu, Z., and Zhang, S. (2008). Research Of Optical Coherence Tomography Microscope Based On CCD Detector, *Proceeding. of SPIE*. Vol. 7156, 71561K–71561K–8.
- Zhao, M., Sha, Y. F., Guo, F., and Yang, M. Q. (2012a). Precision Focal Measuring System Based on CCD Aerial Cameras. *Advanced Materials Research*. 571, 304–307.
- Zhao, M., Sha, Y. F., Guo, F., Zhao, Y., Xie, J., and Han, W. (2013a). Two Methods of Improving the Focus Survey Precision Based on CCD Camera. *Advanced Materials Research*, 710, 438–441.

- Zhao, M., Yang, M. Q., Guo, F., and Sha, Y. F. (2012b). An Automatic Examining-Focus System to Aerial Cameras with CCD. *Advanced Materials Research*, 571, 312–315.
- Zhao, W. H., Duan, Z. Y., Zhao, P., and Zhao, W. Z. (2012c). Study on CCD Measurement System Based on Image Processing. *Advanced Materials Research*. Vols.538-541, 2143–2146.
- Zhao, Y. W., Gao, R., Liu, C. Y., and Zhang, J. (2013b). Design the CCD Tablet Thickness Measurement System Based on Laser Triangulation Method. *Advanced Materials Research*, 748, 521–524.
- Zhong, L. J., and Li, W. W. (2010). A Method Of Online Color-Difference Detecting Based On Image Processing And its Application. *Applied Mechanics and Materials*. Vols. 37-38, 14–17.