IMAGING OF SOLID FLOW IN A GRAVITY FLOW RIG USING INFRA-RED TOMOGRAPHY

MOHD AMRI B MD YUNUS

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Electrical)

Faculty of Electrical Engineering
Universiti Teknologi Malaysia

OCTOBER 2005

aan Mama en Papa

ACKNOWLEDGEMENTS

Praise to Allah S.W.T., the Most Gracious, the Most Merciful, whose blessing and guidance have helped me through my thesis smoothly. There is no power nor strength save in Allah, the Highest and the Greatest. Peace and blessing of Allah be upon our Prophet Muhammad S.A.W. who has given light to mankind.

I would like to express my deepest gratitude to my supervisor Dr. Sallehuddin Ibrahim for his support and supervision. This research would not have been successful without his invaluable guidance, constant help as well as constructive criticisms and opinions throughout the research.

I would like to express my sincere thanks to Pangeran who provided guidance and assistance during the research. Also to the lab assistant, Abang Faiz thanks you for your assistance and support during my research.

Special thanks to my mother, father, brothers, sisters, and families for their assistance and sedulous guidance. Also, thanks to all my friends and syabab, whose sacrifices had made it possible.

Last but not least, to the Ministry of Science, Technology, and Innovations (MOSTI) and Universiti Teknologi Malaysia for providing the funds and allowing me to use the facilities during my research.

ABSTRACT

Information on flow regimes is vital in the analysis and measurement of industrial process flow. Almost all currently available method of measuring the flow of two-component mixtures in industrial pipelines endeavors to average a property of the flow over the pipe cross-section. They do not give information on the nature of the flow regime and they are unsuitable for accurate measurement where the component distribution is spatially or time varying. The overall aim of this project is to investigate the use of an optical tomography method based on infra-red sensors for real-time monitoring of solid particles conveyed by a rotary valve in a pneumatic pipeline. The infra-red tomography system can be divided into two distinct portions of hardware and software development process. The hardware development process covers the infra-red sensor selection, fixtures and signals conditioning circuits, and control circuits. The software development involves data acquisition system, sensor modeling, image algorithms, and programming for a tomographic display to provide solids flow information in pipeline such as concentration and velocity profiles. Collimating the radiated beam from a light source and passing it via a flow regime ensures that the intensity of radiation detected on the opposite side is linked to the distribution and the absorption coefficients of the different phases in the path of the beam. The information is obtained from the combination of two orthogonal and two diagonal light projection system and 30 cycles of real-time measurements. Those information on the flow captured using upstream and downstream infra-red sensors are digitized by the DAS system before it was passed into a computer for analysis such as image reconstructions and cross-correlation process that provide velocity profiles represented by 16×16 pixels mapped onto the pipe cross-section. This project successfully developed and tested an infra-red tomography system to display two-dimensional images of concentration and velocity.

ABSTRAK

Maklumat tentang regim aliran adalah sangat penting di dalam analisis dan pengukuran aliran proses pengindustrian. Hampir kesemua kaedah pengukuran aliran gabungan dua komponen di dalam paip pengindustrian berfungsi untuk mendapatkan purata aliran merangkumi keratan rentas paip. Mereka tidak memberi maklumat asal kawasan aliran dan tidak sesuai untuk pengukuran tepat di mana taburan komponen berubah secara ruang atau masa. Matlamat utama projek ini adalah untuk mengkaji penggunaan kaedah tomografi optik berasaskan kepada penderia infra-merah untuk pengawasan masa-nyata partikel pepejal yang dialirkan oleh injap berputar di dalam satu paip pneumatik. Sistem tomografi infra-merah boleh dibahagikan kepada dua bahagian proses pembangunan iaitu perkakasan dan perisian. Proses pembangunan perkakasan meliputi pemilihan penderia infra-merah, peralatan dan litar penyesuaian isyarat, dan litar kawalan. Proses pembangunan perisian melibatkan sistem perolehan data, pemodelan penderia, algoritma imej, dan pengaturcaraan untuk paparan tomografi di dalam menghasilkan maklumat aliran pepejal di dalam laluan paip seperti profil tumpuan dan halaju. Penumpuan sinar pancaran daripada satu punca cahaya dan melalukannya di dalam kawasan aliran, memastikan kecerahan sinar telah dikesan pada bahagian yang bertentangan berkait kepada taburan dan pekali penyerapan fasa yang berbeza di sepanjang laluan pancaran. Maklumat diperoleh daripada gabungan dua ‘orthogonal’ dan dua ‘diagonal’ sistem projeksi dan 30 kitar pengukuran masa-nyata. Maklumat aliran yang diambil menggunakan penderia infra-merah ‘upstream’ dan ‘downstream’ di digitalkan oleh sistem DAS sebelum memasuki sebuah komputer untuk analisis seperti pembinaan semula imej dan proses sekaitan-silang yang menghasilkan profil halaju yang dipetakan pada 16×16 piksel keratan rentas paip. Projek ini dengan jayanya telah membangunkan dan menguji satu sistem tomografi infra-merah untuk paparan imej dua-dimensi penumpuan dan halaju.

TABLE OF CONTENTS

LIST OF TABLES

TABLE	DESCRIPTION	PAGE

LIST OF FIGURES

FIGURE	DESCRIPTION	PAGE

FIGURE	DESCRIPTION	PAGE

FIGURE	DESCRIPTION	PAGE

FIGURE	DESCRIPTION	PAGE

FIGURE	DESCRIPTION	PAGE

LIST OF ABBREVIATIONS

ADC - Analog to digital conversion

$As_{Tx,Rx}(x',\phi)$ - The total average values for upstream and downstream sensors based on 30 measurement cycles before normalized

$\overline{As_{Tx,Rx}(x',\phi)}$ - The total average values for upstream and downstream sensors based on 30 measurement cycles after normalized

a - Acceleration of gravity (ms^{-2})

$B(x',\phi)$ - Hybrid reconstruction algorithm constant value for each receiver

C - Concentration percentage

CT - Computerized Tomography

$\overline{C_{av}}$ - Total average concentration profile percentage value for 30 cycles

$C_{n,b}$ - Total concentration profile percentage value from each cycle (n) and buffer (b)

DAC - Digital to analog conversion

DAS - Data acquisition system

DI - Digital input

DMA - Direct memory access

DO - Digital output

D_n - Maximum line number of infra-red light beam

$\overline{DT}$ - Total voltage reading from downstream sensors after normalized

$DT_{Tx,Rx}(x',\phi)$ - The total average values for each downstream sensor before normalized

$\overline{D_{T_{Tx,Rx}}(x',\phi)}$	- The total average values for each downstream sensor after normalized
D_T	- The total voltage reading from downstream sensors before normalized
D_n	- Maximum line number of infra-red light beam
$d_{x,y}(t-\tau)$	- Downstream sensor's array profiles values
e_U	- The upstream error
e_D	- The downstream error
$e_{\bar{U}}$	- The normalized upstream error
$e_{\bar{D}}$	- The normalized downstream error
F^{-1}	- 1-dimension inverse Fourier transform
FLBP	- Filtered Linear Back Projection
$f(x, y)$	- An object representations by a two-dimensional function
$\hat{f}(x,y)$	- Approximation of the object function in volts
gn	- The pixel matrix value at the *n* position
K_U	- Upstream scaling factor
K_D	- Downstream scaling factor
K	- Overall scaling factor
$K(\omega)$	- Filter kernel in the frequency domain
LBP	- Linear Back Projection
LED	- Light Emitted Diode
MFR	- Mass Flow Rates
$M_{x',\phi}(x,y)$	- The sensitivity map of infra-red views ($V_{x',\phi}(x,y)$) before the pixels outside the flow pipe are zeroed
NMSE	- Normalized mean square error
$N(x',\phi)$	- Normalized sensor reading during flow condition for each flow model
PSNR	- Peak signal to noise ratio
PT	- Processing time
P_T	- The total voltage reading from expected values
$P_{Tx,Rx}(x',\phi)$	- The expected value which has been rescaled

$p_{\phi}(x_1')$	- Projection data for AB line
$p_{\phi}^{*}(x')$	- Convolved projection data in time domain
R_{mak}	- Maximum cross-correlation function value
$S_{\phi}(x,y)$	- Sensitivity map for each projection
$S_{\max}(x,y)$	- Total distribution of the infra-red light beam in a specific rectangle
$\overline{S_{\phi}(x,y)}$	- Normalized sensitivity map for each projection
s	- Distance(m)
T_{op}	- Total number of pixels occupied by any infra-red light from all infra-red transmitters
t	- Time (s)
U_T	- The total voltage reading from upstream sensors before normalized
$\overline{UT}$	- Total voltage reading from upstream sensors after normalized
$UT_{Tx,Rx}(x',\phi)$	- The total average values for each upstream sensor before normalized
$\overline{UT_{Tx,Rx}(x',\phi)}$	- The total average values for each upstream sensor after normalized
u	- Initial velocity (ms^{-1})
$u_{x,y}(t)$	- Upstream sensor's array profiles values
V	- Measured velocity value
V_t	- Calculated velocity value (theoretically)
V_{TX}	- Digital signal for infra-red transmitter circuit
V_{Sup}	- Digital signal for upstream sample and hold circuit
V_{Muxup}	- Digital signal for upstream sample and hold circuit
V_{Sdown}	- Digital signal for downstream sample and hold circuit
$V_{Muxdown}$	- Digital signal for downstream sample and hold circuit
V_{Trig}	- Digital signal inserted into TGIN data acquisition system terminal
V_{Burst}	- Digital signal inserted into XPCLK data acquisition system terminal

$V_{refTx,Rx}(x',\phi)$	- Sensor reading for view from emitter Tx to receiver Rx during no-flow (V)
V_{cal}	- The standardized/calibrated value of each view that was assumed to be 5V
$Vs_{Tx,Rx}(x',\phi)$	- Amplitude of signal loss from receiver from *Tx* to *Rx* view
$V_{Tx,Rx}(x',\phi)$	- Received signal from transmitter during flow-condition
$V_{x',\phi}(x,y)$	- The sensitivity map of infra-red views ($V_{x',\phi}(x,y)$) before the pixels outside the flow pipe are zeroed
$v(x,y)$	- Velocity profile
wn	- The convolution-filter mask value at the *n* position
x'	- Detector coordinate in the investigated area
$x1'$	- Detector coordinated in the scaled investigated area
x'_1	- The coordinate of AB line in *x'* plane
$(x1, y1)$	- Scaled spatial domain
$(x1', y1')$	- Scaled projection domain
$x1'_{0,1...t}$	- The receivers' positions in the scaled projection domain, where *t* = 10
μ	- Permeability
σ	- Conductivity
τ_m	- Transit time
ϕ	- Projection angle
%e	- Error of velocity value compared to the calculated velocity value

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Wilhelm Roentgen discovered x-rays in the year 1895, his discoveries contributed to the most important diagnostic methods in modern medicine. Since then, it is possible to look through into both non-living and living things without cutting the certain area of the subject by taking X-ray radiography (Ellenberger *et al.*, 1993). This method of projection is far from being a perfect image of the real subject since the images were a superposition of all planes normal to the direction of X-ray propagation. In the 30's conventional tomography was the tomographic method using the X-ray radiation and gave possibility to restore information of 2D and 3D images (William and Beck*,* 1995).

The word 'tomography' is derived from the Greek words, where 'tomo' meaning 'to slice'/'section' and the word 'graphy' means image. In the year 1970 all the possibilities in the 30's became true when this technique utilized the x-rays to form images of tissues based on their x-ray attenuation coefficients. However, this technique does not stop at the medical studies area and it was successfully developed into the industrial field and commonly known as the Industrial Process Tomography (IPT). This technique aims to measure the location concentration, phase proportions, and velocity measurement (Chan, 2003) retrieved from the quantitative interpretation of an image or, more likely, many hundreds of images corresponding to different spatial and temporal conditions using direct measurement/real time due to the dynamic changes of internal characteristic.

There are many parameters such as 2D and 3D images, velocity, and Mass Flow Rates (MFR) which can be retrieved from the tomography visualizing techniques within the processor or unit operation. Hence, the latter parameters give the information of the distributions of material in a pipeline. Therefore, from the knowledge of material distribution and material movement, a mathematical model can be derived and it can be used to optimize the design of the process (Tapp *et.al*, 2003).

1.1 Background of Problems

Process Tomography has become one of the vast growing technologies nowadays The tomographic imaging of objects offers a unique opportunity to unravel the complexities of structure without the need to invade the object (Beck and Williams, 1996). It is a diversification from the original research on x-ray tomography, which focused on how to obtain 2-D cross-section images of animals, human, and non-living things (Syed Salim, 2003). Process Tomography can be applied to many types of processes and unit operation, including pipelines (Neuffer *et al.*, 1999), stirred reactors (Wang *et.al*, 1999), fluidized bed (Halow and Nicoletti, 1992), mixers, and separator (Alias, 2002). Process tomography is an essential area of research involving flow imaging (image reconstruction) and velocity measurement. For example in the research that was carried out by Ibrahim (2000), the Linear Back projection (*LBP*) algorithm which was originally designed for x-ray tomography was used to obtain the concentration profiles of bubbles in liquid contained in a vertical flow rig. This project investigated the two-phase flow (solid particle and air) using a vertical pneumatic conveyor flow rig.

Flow imaging usually involved obtaining images of particles and gas bubble (Yang and Liu, 2000) and the measurements can be either done using on-line (real time) or off-line. For on-line measurement, there are many performance aspects that must be considered such as hardware performance, data acquisition (signal interfacing), and algorithm performance. Limited numbers of measurement affect the quality of images obtained. The input channel of the data acquisition system has to be increased with the increase in the number of sensors used.

LBP algorithm is the most popular technique that was originally applied in medical tomography. Research conducted by Chan (2003) improved flow imaging using 16 alternating fan-beam projections with an image reconstruction rate of 20 fps, but this image reconstruction rate not is sufficient to achieve an accurate measurement of velocity. Generally, this project performed an investigation on how to improve the sensing method developed by Abdul Rahim (1996) which used fiber optics in flow visualization. Instead of using one light source, this project focused on using individual light source meaning one infra-red LED emitter for one photodiode. This method was then combined with an infra-red tomography system which consist of a hardware fixture, a signal conditioning system, and a data acquisition system by synchronizing the whole process operation.

Furthermore, image reconstruction in the spatial domain and frequency domain were investigated for this project. Generally, the information retrieved from the measurement system can be used to determine both the instantaneous volumetric and velocity of solids over the pipe cross section.

1.2 Problem Statement

The process tomography system requires the knowledge of various discipline such as instrumentation, process, and optics to assist in the design and development of the system. Generally, the solutions to the problems that were carried out in this project are:

- Development of a suitable sensor configuration for the selected infra-red emitter and receiver. Design of the fixture must be able to avoid the infra-red sensor from being exposed to any kind of ambient light (day light, lamp etc) and placed around the boundary of the pipe so that light emitted from the emitter will be the only one that is in contact with the solid particle in the pipeline.

- Determine the best infra-red emitter and receiver based on the physical nature of the design of material that is involved in the transmission of the infra-red light, light emission, spectral characteristic, sensor radiation characteristic, receiver respond, optical power, and availability from suppliers.

- Selecting suitable signal conditioning and electronic controller. The characteristic of the component used will determine the whole measurement result, such as power consumption, offset current, input impedance, slew rate, and common mode input voltage range (Tan, 2002).

- Increasing the number of sensor measurement (128 pairs of infra-red transmitter and receiver for upstream and downstream planes). The number of measurement and projection angle subsequently affect the quality of the image reconstructed (Ibrahim, 2000).

- Synchronization of the data acquisition with the circuitry operation. A digital controller with sufficient of memory, easy programming language, programmable, stable, and has a high operation speed.

- The programming language that drive and control the interface between the hardware developed must be compatible with the application programming language in Windows environment.

- Implementation of the image reconstruction algorithm and velocity measurement. The image reconstruction estimated the distribution of material within the pipe which would provide the measured sensor output and the velocity measurement provide the solid particles velocities values.

The idea based on Hartley *et al.* (1995) and Chan (2003) where the method of research covers:

- Two orthogonal parallel projections those are perpendicular to each other.

- The design of the system started with the aim of flow imaging.

- The output of several sensors for each projection are multiplexed, in order to minimize the system complexity and cost.

- Hartley's system (Hartley *et al*., 1995) made use of 8 × 8 sensors, in which each projection has 8 views for image reconstruction, but when larger number of views are needed it has to be determined off-line since the transputer being used was slow.

In conjunction with the previous research, the solutions required are listed as follow:

- The SFH485P infra-red LED transmitter and the SFH203P photodiode receiver selected have a matching wavelength at 990nm, a flat top surface for full light collimation before it is distributed using fiber optics, fast switching characteristic, and low optical power.

- The appropriate technique of constructing the signal conditioning circuit where it is very important to convert the amount of incident infra-red light using the photodiode to a suitable voltage level. Then a sample and hold circuit will be used to hold the measured signal.

- Increase the numbers of view/measurement by optimizing the time required to capture 128 sensor channels, using a data acquisition system with 64 analog input channels.

- Synchronization between signal conditioning and data acquisition, using a PIC controller where the operation between the data acquisition system and circuitry operation that involved settling time for hold and sample must be configured to make sure data obtained from upstream and downstream sensors can be differentiate.

- The Microsoft Visual C++ 6.0 was selected because the C language has the advantages of being small size, fast, support modular programming, and memory efficient (Bronson, 1999). Microsoft Visual C++ 6.0 is a powerful language with a standard user interface and enables device independent program.

- A software driver for real-time data acquisition in the Microsoft Window environment called DriverLINX provided by Keithley customized to support the data acquisition system interface system between the software and hardware developed.

- Solving the forward and reverse problem based on the projection theorem. The forward problem provides the theoretical output of each sensor under no-flow and flow conditions when the sensing area is considered to be two-dimensional and the inverse problem estimates the distribution of material within the pipe which would provide the measured sensor outputs (Ibrahim *et al.*, 1999).

- Numerous image reconstruction technique adapted in the tomography, such as Linear Back projection and Fourier reconstruction. In this study the reconstruction, covered image reconstruction in the spatial domain, frequency domain, and the hybrid approach (Ibrahim, 2000).

- The application of cross correlation technique for velocity measurement.

1.3 Significance and Objective of the Study

Uchiyama *et al.* (1985) pointed out that the use of thermography is an inappropriate technique for measuring the temperature distribution in flames, as the infra-red radiation received by the sensor is the line integral of the emitted radiation along the optical path. Infra-red radiation, having wavelengths which are much longer than visible light, can pass through dusty regions of space without being scattered. This means that we can study objects hidden by gas and dust in the infra-red, which we cannot see in visible light (Mass, 1972). These are the advantages using infra-red light where the dust or gas that is produced or fetched by the conveyed particles does not affect the measuring systems.

Studies have shown that both contrast and spatial resolution of optical images are affected by the optical properties of the background medium, and high absorption and scattering are generally beneficial. Based on these observations, wavelengths shorter could be profitable for optical measuring systems (Taroni *et al.*, 2004). X-rays, gamma-rays, and ultraviolet-light have a shorter wavelength but the problems arise on how to handle properly this kind of material because it's dangerous to living things.

Research by Ibrahim *et al.* (1999) has proved that the use of fiber optic can enhance the image resolution with the purpose of measuring the concentration and velocity of gas bubbles in a vertical water column. Chan (2003) utilized the concept of fan beam switching mode to increase the total projections, image resolution and the total number of measurements to analyze images of solid particle flow. Pang (2004) developed an optical tomography system to perform real-time mass flow rate by using two local networked PC and five programs. Based on those researches, the tomography system in this project can enhance the image resolution, increase the total number of measurements in order to image the flow of solid particles and perform velocity measurement based on the use of fiber optic and parallel beam switching mode between the measurement planes using one PC and one programs (upstream and downstream planes).

The objectives of this investigation are:

1) To become familiar with the concept of process tomography, and associated sensors.

2) To understand the application of data acquisition system and tomographic imaging reconstruction.

3) To study the interaction between the collimated infra-red light and the targeted object (which is dropped into the flow pipe).

4) To solve the forward and reverse problems (Ibrahim, 2000).

5) To calculate the velocity of dropping particle using results from the cross correlation method (Plaskowski *et al.,* 1997) and free fall motion.

6) To design a hardware system for the infra-red tomography system.

7) To incorporate the signal conditioning (circuitry operation) with the data acquisition system by synchronizing the signal conditioning with the data sampling processes.

8) To determine the better reconstruction algorithm for flow imaging between spatial domain, frequency domain, and hybrid image reconstruction.

9) To implement a measurement system that will obtain data from the infra-red sensors for concentration and velocity measurements for various flow rates.

10) To test this system on a pneumatic flow conveyor by distributing solid particles into a vertical pipe and to investigate the concentration and velocity profiles using the experimental data that have been obtained for various flow rates.

1.4 Scope of Study

The aim of the study is to investigate the flow regimes (image reconstruction) and flow velocity in pipe due to dropping particles and velocity measurement (Kaplan, 1993) using a conveyor flow rig. The scope of study includes:

1) Absorption by the emission of infra-red light.

2) Flow rates, concentration profiles, and velocity of dropping particles.

3) Signal conditioning and data acquisition system.

4) Process modeling: includes sensors fixture, flow rig model, signal conditioning circuit's design and software development.

5) Image reconstruction algorithm and cross-correlation method.

6) Thesis writing.

1.5 Organization of the Thesis

Chapter 1 presents an introduction on process tomography research's background problem, problem statement, significance and objective and scope of study.

Chapter 2 presents a brief review of process tomography, types of process tomography such as electrical capacitance, electrical impedance, ultrasonic, x-ray, nuclear resonance magnetic, positron emission, mutual inductance, microwave, and optical tomography.

Chapter 3 presents a discussion on the relationship between projection and object functions, modeling of the infra-red optical system sensor, software signal conditioning, image reconstruction algorithm, reconstructed image error measurement, and velocity of flow.

Chapter 4 discusses a presentation on the development of infra-red tomography measuring system.

Chapter 5 presents a discussion on the single pixel flow, multiple pixels, half, and full flow modeling, image reconstruction algorithm for flow models, results of reconstructed model images, comparison of algorithms performance, and conclusion from the results.

Chapter 6 presents a discussion on the concentration measurement and the concentration profiles.

Chapter 7 presents a discussion on the introduction of free fall and air resistance theory, velocity measurement, and velocity measurement.

Chapter 8 presents the conclusion and the recommendations for future work.

[illegible] R.[illegible] (1986). [illegible]
[illegible] 585-8.

[illegible] (1990). *Operational Amplifier, Applications, Troubleshooting, and Design.* [illegible]

[illegible] (1995). [illegible] R. A. [illegible]
(ed.) *Process Tomography – Principles, Technique and Application.* [illegible]: [illegible] 151-165.

[illegible] (1991). [illegible]
[illegible] *Int. J. Imaging System and Technology. 2*:144-156.

[illegible] (1974). *The Fast Fourier Transform.* [illegible]

[illegible] (1999). *C++ for Engineers and Scientists.* [illegible]

[illegible] R[illegible] (1996). [illegible]
[illegible] *Meas. Sci. Technol.* [illegible] 396-405.

[illegible] R, [illegible] (1999). *Medical Physics and Biomedical Engineering.* [illegible]

[illegible] (2003). *Real Time Image Reconstruction for Fan Beam Optical Tomography System.* [illegible]

[illegible] R. (1996). *Dual Modality Tomography for the Monitoring of Constituent Volumes in Multi-Component Flows.* [illegible]
[illegible]

[illegible] (1995) [illegible] *Process Tomography – Principles, Technique and Application.* [illegible] 63-83.

[illegible] (1994) *An optical instrumentation system for the imaging of two-component flow.* [illegible]

[illegible] (1996) [illegible] *Meas. Sci. Technol.* [illegible] 343-353.

[illegible] (1993) [illegible] 82 m[illegible] *Meas. Sci. Technol.* [illegible] 874-880.

[illegible] (1999) *C++ Algorithm for Digital Signal Processing.* [illegible]

[illegible] (2002) [illegible] *Chemical Engineering Journal*.86:243-250.

[illegible] (1996) [illegible] *Meas. Sci. Technol.Instrum.* [illegible] 827-837.

[illegible] (1995) *Photodiode amplifiers – Op amp solutions.* [illegible]

[illegible] (1997) *Knowledge-Based Image Processing Systems.* [illegible]

[illegible] (1999). [illegible]
[illegible]
[illegible] *Proc. 1st World Congress on Industrial Process Tomography. Buxton*. 202-209.

[illegible] R., [illegible] R., [illegible] K., [illegible] (1996). [illegible] *Meas. Sci. Technol.* [illegible] 1922.

[illegible] (1992). [illegible] *Powder Technol.* [illegible] : 255-7.

[illegible] R. (1983). [illegible] 483-443.

[illegible] (2002). [illegible] *Meas. Sci. Technol.* [illegible] 73-83.

[illegible] R., [illegible] R., [illegible] (1995). [illegible] *Process Tomography – Principles, Technique and Application*. [illegible] 183-197.

[illegible] J., [illegible] R. (1986). [illegible] *Nucl. Instrum. Methods*. 253: 145-157

[illegible] (1980). *Image Reconstruction from Projection.* [illegible]

[illegible] (1995) [illegible] [illegible]. [illegible]
[illegible] : [illegible] 120-149.

[illegible] (1986) [illegible] *J. Phys. E: Sci. Instrum.* [illegible] 173-177.

[illegible] (2000) *Measurement of Gas Bubble in a Vertical Water Column Using Optical Tomography.* [illegible]

[illegible] R., [illegible] R., [illegible] A (1999) [illegible] *1st World Congress on Industrial Process Tomography*, [illegible] 4-17.

[illegible] (2001) [illegible] *Meas. Sci. Technol.* [illegible] : 1109-1119.

[illegible] (1973) *IC Op-Amp Cookbook.* [illegible]

[illegible] R. (2001) [illegible] *Meas. Sci. Technol.* [illegible] : 1061-1068.

[illegible] (1999) *Principle of Computerized Tomography Imaging.* [illegible]

[illegible] (1993). [illegible]
[illegible] *SPIE.* [illegible]
[illegible] 360-365

[illegible] (2001). *Technical Reference Manual.* [illegible]
[illegible]

[illegible] (2001). *"Op Amps for Everyone".* [illegible]

[illegible] (1995). *Image Processing (Theory, Algorithms, and Architectures).* [illegible]

[illegible] (1972). *Basic Infra-red Spectroscopy.* [illegible]

[illegible] (1995). [illegible]
[illegible] *Process Tomography – Principles, Technique and Application.* [illegible] 539-548.

[illegible] (1984). [illegible]
Academic Press Inc, [illegible] 1-14 [illegible] 82-186.

[illegible] (2002). *Image Reconstruction Using Transmission-mode of Ultrasonic Tomography In Water-Particles Flow.* [illegible]
[illegible]

[illegible]
R.A. (1999). [illegible] *Proceedings of 1st World Congress on Industrial Process Tomography.* [illegible] 177.

[illegible] (1989). *Industrial Microwave Sensors.* [illegible]
[illegible]

[illegible] (1996). [illegible]
[illegible] *Meas. Sci. Technol.* [illegible] : 325-337.

[illegible] (2004). *Real-Time Velocity and Mass Flow Rate Measurement Using Optical Tomography*. [illegible]

[illegible] (1996). [illegible] *Meas. Sci. Technol.Instrum.* [illegible] 287-296.

[illegible] (1995). [illegible] *Process Tomography – Principles, Technique and Application*. [illegible] 85-100.

[illegible] (1994). [illegible] 537. *Data Sheet*. [illegible]

[illegible] (1997). *Imaging Industrial Flows*. [illegible]

R[illegible] R., [illegible] R., [illegible] (1999). [illegible] *Proceedings of 1st World Congress on Industrial Process Tomography*. [illegible] 17-21.

R[illegible] (2003). [illegible] *Meas. Sci. Technol.* [illegible] (4): 199-204.

[illegible] (2003). *Concentration Profiles and Velocity Measurement Using Ultrasonic Tomography*. [illegible]

[illegible] (1995). *Principle of Medical Imaging*. [illegible]

[illegible] (2002). *Velocity Measurement of Solid Particle in Pneumatic Conveyor using Optical and Ultrasonic Sensor via Cross Correlation Method*. [illegible]

[illegible] (1998). [illegible]
Meas. Sci. Technol. [illegible]: 592-598.

[illegible] (2003). [illegible] *Sensors and Actuators B*. [illegible] 17-24

[illegible] udu, R. (2004). [illegible] 1203-1215.

[illegible] (1985). [illegible] *Appl.Opt*, 24:4111-4116

[illegible] (1972). *Practical Application of Infrared Techniques.* [illegible]

[illegible] (1999). [illegible] *Proceedings of 1st World Congress on Industrial Process Tomography*. [illegible] 88-83.

[illegible] (2002). [illegible] *Meas. Sci. Technol.* [illegible]: 1884-1889.

[illegible] (1992). *The Physics of Medical Imaging*. [illegible]

[illegible] (1995). [illegible] *Process Tomography – Principles, Techniques and Application*. [illegible] 3-12.

[illegible] R. A. [illegible] (1997). *Process Tomography, Principles, techniques and applications.* [illegible]

[illegible] (1995). [illegible] R. A. [illegible]. *Process Tomography – Principles. Techniques and Application.* [illegible] : [illegible]. 1995. 281-323.

[illegible] (1993). [illegible] 218-212

[illegible] J. (1995). [illegible] *Meas. Sci. Technol.* 6 (5) : 515-537.

[illegible] (2005). [illegible] *Sensors and Actuators.* B 104:324-331.

[illegible] (1996). [illegible] *Meas. Sci. Technol.* 7 (6) : 853-858.

[illegible] (2000). [illegible] *Flow Measurement and Instrumentation.* [illegible] : 237-244.

[illegible] R. [illegible] R. (2000). [illegible] *Chemical Engineering Journal.* 77:137-142.