EMBEDDED SYSTEM BASED SOLID-GAS MASS FLOW RATE METER USING OPTICAL TOMOGRAPHY

CHIAM KOK THIAM

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Universiti Teknologi Malaysia

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To my beloved father and mother

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ABSTRACT

Monitoring solid-gas flow in terms of flow visualization and mass flow rate (MFR) measurement is essential in industrial processes. Optical tomography provides a method to view the cross sectional image of flowing materials in a pipeline conveyor. Important flow information such as flow concentration profile, flow velocity and mass flow rate can be obtained without the need to invade the process vessel. The utilization of powerful computer together with expensive Data Acquisition System (DAQ) as the processing device in optical tomography systems has always been a norm. However, the advancements in silicon fabrication technology nowadays allow the fabrication of powerful Digital Signal Processors (DSP) at reasonable cost. This allows the technology to be applied in optical tomography system to reduce or even eliminate the need of personal computer and the DAQ. The DSP system was customized to control the data acquisition of 16x16 optical sensors (arranged in orthogonal projection) and 23x23 optical sensors (arranged in rectilinear projections) in 2 layers (upstream and downstream). The data collected was used to reconstruct the cross sectional image of flowing materials inside the pipeline, velocity profile measurement and mass flow rate measurement. The mass flow rate result is sent to a Liquid Crystal Display (LCD) display unit for display. For image display purpose, the reconstructed image was sent to a personal computer via serial link. In the developed system, the accuracy of the image reconstruction was increased by 12.5% by using new hybrid image reconstruction algorithm. The processing time required to obtain flow velocity was 12 times faster by using Sensor To Sensor cross correlation in frequency domain instead of Pixel to Pixel cross correlation in time domain. By optimizing the overall system, the developed system is capable of producing a Mass Flow Rate measurement in only 430 ms.

ABSTRAK

Pengawasan aliran pepejal-gas dari segi gambaran aliran dan pengukuran kadar aliran jisim adalah penting dalam proses industri. Tomografi optik menyediakan satu kaedah untuk melihat gambaran keratan rentas aliran bahan dalam paip. Maklumat penting aliran seperti profil kepadatan, kelajuan aliran dan kadar aliran jisim boleh diperolehi tanpa perlu mencerobohi paip proses. Penggunaan komputer berkuasa tinggi bersama-sama dengan Sistem Pemerolehan Data yang mahal sebagai perkakasan pemproses dalam tomografi optik sudah menjadi kebiasaan. Walau bagaimanapun, kecanggihan dalam teknologi penghasilan silikon kini membolehkan penghasilan Pemproses Isyarat Digital yang berkuasa tinggi pada kos yang berpatutan. Ini membolehkan teknologi ini diaplikasikan dalam tomografi optik bagi mengurangkan atau mengelakkan sama sekali pergantungan pada komputer dan Sistem Pemerolehan Data. Sistem Pemproses Isyarat Digital dikonfigurasikan untuk mengawal proses pemerolehan data bagi 16x16 sensor optik (disusun dalam projeksi 'orthogonal') dan 23x23 sensor optik (disusun dalam projeksi 'rectilinear') pada 2 lapisan (atas dan bawah). Data yang dikumpul digunakan untuk menghasilkan gambaran keratan rentas aliran bahan dalam paip, pengukuran profil kelajuan dan pengukuran kadar aliran jisim. Keputusan kadar aliran jisim dihantar ke unit pemapar untuk tujuan paparan. Untuk tujuan gambaran imej, imej yang dihasilkan dihantar ke komputer melalui talian sesiri. Dalam sistem yang dihasilkan, ketepatan imej yang dihasilkan meningkat sebanyak 12.5% dengan menggunakan algoritma hibrid pembentukan semula image yang baru. Tempoh pemprosean yang diperlukan untuk mendapatkan kelajuan aliran adalah 12 kali lebih laju dengan menggunakan Korelasi Sensor Ke Sensor dalam domain frekuensi berbanding Korelasi Pixel Ke Pixel dalam domain masa. Dengan mengoptimakan keseluruhan sistem, ia mampu mengukur setiap Kadar Aliran Jisim dalam tempoh 430 ms sahaja.

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LIST OF SYMBOLS / ABBREVIATIONS

ADC	-	Analogue to Digital Converter
ALU	-	Arithmetic Logic Unit
ASIC	-	Application Specific Integrated Circuit
bps	-	Bit Per Second
CAN	-	Controller Area Network
CODEC	-	Coder Decoder
CPU	-	Central Processing Unit
DAC	-	Digital to Analogue Converter
DFT	-	Discrete Fourier Transform
DIF	-	Decimation In Frequency
DIT	-	Decimation In Time
DSP	-	Digital Signal Processor
ECT	-	Electrical Capacitance Tomography
EEPROM	-	Electrical Erasable Programmable Read Only Memory
EIT	-	Electrical Impedence Tomography
EPROM	-	Electrical Programmable Read Only Memory
FFT	-	Fast Fourier Transform
FPGA	-	Field Programmable Gate Array
FPU	-	Floating Point Unit
GPIO	-	General Purpose Input Output
GUI	-	Graphical User Interface
HC11	-	M68HC11 micro controller
HPI	-	Host Processor Interface
Hz	-	Hertz
IFFT	-	Inverse Fourier Transform
ISR	-	Interrupt Service Routine
LCD	-	Liquid Crystal Display

LED	-	Light Emitting Diode
LSB	-	Least Significant Bit
MAC	-	Multiply and Accumulate
MFR	-	Mass Flow Rate
MIPS	-	Million Instructions Per Second
MRI	-	Magnetic Resonance Imaging
ms	-	mili seconds
MSB	-	Most Significant Bit
MSPS	-	Mega Samples per Second
NMR	-	Nuclear Magnetic Resonance
PC	-	Personal Computer
PCB	-	Printed Circuit Board
PSoC	-	Programmable System on Chip
PT	-	Process Tomography
PTP	-	Pixel To Pixel
RAM	-	Random Access Memory
RFFT	-	Fast Fourier Transform for Pure Real Signals
SAC	-	Successive Approximation Conversion
SCI	-	Serial Communication Interface
SPI	-	Serial Peripheral Interface
SRAM	-	Static Random Access Memory
STS	-	Sensor To Sensor
us	-	micro seconds
USART	-	Universal Serial Asynchronous Receiver Transmitter
USB	-	Universal Serial Bus

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CHAPTER 1

INTRODUCTION

1.1 Process Tomography Overview

The term tomography originated from two Greek words which were '*tomos*' and '*graph*'. '*Tomos*' means slice while '*graph*' means picture. Thus, the term tomography means a slice of a picture (Rahim and Green, 1997). In other words, tomography can be defined as an approach to visualize the cross sectional image of an object (Pang, 2004a). The concept of tomography was first applied in medical field to diagnose lung disorders in the early 1930s (Dickin *et al.*, 1992). Two commonly known tomography system used for medical diagnosis are X-ray tomography and the Magnetic Resonance Imaging (MRI).

During year 1980's, researchers from University of United Manchester Institute of Science and Technology (UMIST) began to apply the concept of tomography into industrial process monitoring system; where the investigated objects were the pipeline conveyors and process vessels. This field of application is commonly known as Industrial Process Tomography (IPT) or Process Tomography (PT) (Pang, 2004a). Important flow information such as flow concentration, flow velocity and mass flow rate can be determined without the need to invade process or object. This information helped industries in monitoring, verifying and improving their pipeline conveyor and process vessels operation (Leong, 2004). In this research, knowledge in process tomography had been applied as the main concept to perform mass flow rate measurement.

1.2 Background Problems

The full automation of solid-handling plant has frequently not been possible because of the lack of a basic flow meter. Previously used technique to measure solid flow often involved removing the material for weighing which was complicated, expensive and did not allow continuous feedback for automatic control (Green *et al.,* 1978). Many non intrusive techniques attempted to measure solids mass flow in pneumatic conveyor were elaborated by Beck *et al*. (1987).

Later, Xie *et al.* (1989) made an effort to measure mass flow of solids in pneumatic conveyor by combining electrodynamics and capacitance transducers. Rahim *et al.* (1996) investigated applications of fibre optics into optical tomography for flow concentration measurement. Chan (2002) followed up and investigated mass flow rate measurement using optical tomography by relating the flow's concentration profile measurement with its mass flow rate. This method first performs calibration by recording the flow's concentration percentage plotted against mass flow rate measured using weight scale and stop watch. Based on their findings, the two variables had linear relation in light flow condition. However, this technique requires re-calibration each time a new flow material is used.

Cross correlation technique was proposed by Beck *et al.* (1987) for flow velocity measurement. This function was successfully applied by Ibrahim and Green (2002a) for offline bubble flow velocity measurement using optical tomography. In 2003, Pang (2004a) implemented real time system for solid-gas flow concentration, flow velocity and mass flow rate measurement using optical tomography and data distribution system. The cross correlation techniques being used by these researches were based on time domain cross correlation function, which was very time consuming.

Pang (2004a) implemented four projections arrays (2 orthogonals and 2 rectilinears) in optical tomography system. The extra two layers (the Rectilinear layers) were used to filter the ambiguous image and smearing effects. However, analogue acquisition was used to acquire all the measurements. The obtained data from masking layer were used for comparison to predetermined threshold values. Using this method, valuable time was utilized for analogue to digital conversions. Furthermore, the number of sensors on the rectilinear was quite large. Although the research successfully implemented real time optical tomography system, it required four powerful personal computers and a network hub in order to implement data distribution system. The resulting system was large and not easily portable.

1.3 Problem Statements

i. Data acquisition and analysing data in optical tomography requires fast digitizer and high performance computing power. In order to eliminate the use of expensive Data Acquisition System for sensor measurements and a powerful computer for data analysis, a high performance embedded system need to be designed and implemented. This embedded system must be able to perform data acquisition, analyse the measured data and support standard communication protocols. It is also the main controller for the overall operation.

ii. Signal measurement using Analogue to Digital Converter requires very long time, especially when the number of sensors is large. Alternative method such as voltage comparator to digitally sample signals on masking layer need to be investigated and applied. A method to send the measurements quickly to the embedded system also needs to be designed and implemented.

iii. Algorithms in processing acquired measurement data such as Pixel to Pixel correlation to obtain flow velocity is very computation intensive especially in this research where two layers of sensors totalling up to 156 sensors are used. Performing cross correlation to obtain velocity profile with only one hundred sets of data already requires thousands of calculations. New techniques and algorithms need to be investigated to reduce the processing time required in order to achieve a high performance system.

iv. The implementation of this research without using a computer as the main controller hinders user from changing settings or viewing results acquired from the embedded system. Therefore, a user interface unit need to be designed and implemented for user input and output processing. Besides that, a tomography system without flow visualization seems odd. Therefore, a GUI need to be developed to serve the purpose of displaying information for debugging and flow monitoring.

v. Programming techniques affects the performance of an embedded system significantly. Deep understanding of memory architecture in the embedded system and code execution is required to develop optimized firmware for the system.

1.4 Importance of Study

The automation of solid material handling may be realized in the near future by having an instrument that is able to provide online solid-gas mass flow rate measurement. Online measurement eliminates the need for removing material for weighing which is complicated and expensive. Previous method of mass flow rate measurement using inverse solution of concentration measurement (Chan, 2002) requires calibration each time a new material is used or there is modification to the flow rig. This research aims to implement algorithm based mass flow rate measurement which will not require any calibration constant.

The implementation of this research using embedded systems results in a solid-gas mass flow rate meter that is small and portable. The overall cost will also be significantly reduced compared to using standard Data Acquisition System and powerful computers (Pang, 2004a). For industrial applications that are only interested in the mass flow rate measurement, the result can be seen on a LCD. On the other hand, the instrument is also capable to visualize the material flow by connecting the instrument to a laptop via standard serial communication interface (RS 232). The Graphical User Interface installed on the laptop will display the current reconstructed image, mass flow rate measurement or sensor values for data logging or monitoring purpose.

Velocity profile was previously obtained using cross correlation in work by Xie *et al.* (1989), Ibrahim and Green (2002a) and Pang (2004a). Pixel to pixel correlation and sensor to sensor correlation were investigated by Ibrahim using offline system. Later, Pang implemented online system with real time measurement. Both Ibrahim and Pang showed that the periphery velocity could be obtained by cross correlating the upstream sensor layer with the downstream sensor layer. The fact that sensor to sensor correlation is much faster than pixel to pixel correlation motivates investigation of using the periphery velocity to obtain the velocity profile. By using this technique, significant amount of processing time can be reduced and therefore the overall system performance can be increased too.

The cross correlation technique used in this research is optimized by performing the calculations in frequency domain (known as Fast Convolution). Commonly, cross correlation is performed in time domain as it is less complicated and resembles a direct implementation of the cross correlation equation. By performing Fast Convolution, the processing time required to obtain velocity result reduces considerably as the number of cross correlation elements becomes larger. Noting that the input sequences for the cross correlation function are pure real values (not complex values) from the sensor data, the cross correlation function is optimized further using Fast Fourier Transform for pure real sequences (RFFT). This again reduces the processing time required to convert the data to frequency domain. In short, the results obtained from these investigations of using sensor to sensor cross correlation technique together with performing optimized cross correlation in frequency domain will significantly reduce the time required per mass flow rate measurement.

Last but not least, the development of the firmware for the embedded systems was optimized to achieve highest speed possible. Function calls, algorithms implementations and communication between sub systems were all developed with considerations for accuracy and optimum performance. These optimizations are very important as they affect the overall performance considerably.

1.5 Research Objectives

This research aimed to develop an embedded system based solid-gas mass flow rate meter using optical tomography technique. This research was carried out according to the following objectives:

i. To implement embedded system as the main controller in an optical tomography system for the purpose of data acquisition, data analysis and result display.
ii. To increase data acquisition rate by using high speed ADC for analogue sensor measurements and voltage comparators for sensors on masking layer.
iii. To optimize the performance of hybrid image reconstruction algorithm in terms of accuracy and processing speed when carried out on embedded system.
iv. To investigate the application and performance of cross correlation function carried out in frequency domain to obtain flow velocity.
v. To investigate the application and performance of sensor to sensor cross correlation results in reconstructing flow velocity profile.
vi. To implement algorithm based mass flow rate measurement using embedded system.
vii. To investigate the performance of the overall system in carrying out image reconstruction, velocity profile measurement and mass flow rate measurements.
viii. Finally, restudy the research result and make necessary suggestions and recommendations for further improvement.

1.6 Research Scopes

The scope of this research can be categorized as follows:

i. The developed embedded system should have capability to process instructions at high speed, perform digital inputs and outputs, support standard communication protocols (SPI, SCI) and contain sufficient memory to store program and large amount of measurement data.

ii. Two signal conditioning circuits will be designed for digital sampling and analogue sampling. Digital sampling is used for masking purpose while the analogue sampling is needed to reconstruct the cross sectional image of the flowing material. The Signal Conditioning Unit must be able to multiplex 64 analogue signals to ADC channels and 92 binary data to SPI channel on the embedded system.

iii. The developed User Interface Unit will be able to decode keypad press and drives a 2-line, 16-character Liquid Crystal Display (LCD) panel to show the mass flow rate result and system settings. This unit should support RS 232 communication with the main controller and perform user input and output with minimum dependency to the main controller.

iv. The developed PC Graphical User Interface (GUI) software should display information for debugging such as sensor values and current settings for the embedded system. Flow monitoring should also be supported by enabling the display of current reconstructed image and mass flow rate result. The interface between the GUI and the embedded system is based on standard RS 232 serial interface.

v. The performances of algorithms and implementations of velocity profile construction using sensor to sensor correlation, pixel to pixel correlation, processing in time domain and processing in frequency domain are investigated.

vi. The overall system should be optimized to perform image reconstruction, velocity profile measurement and mass flow rate measurement using programming techniques.

vii. Results obtained should be verified by comparing between experiment results to theoretical calculations.

1.7 Thesis Organization

Chapter 1 provides an introduction to process tomography, research objectives, background problems, scope of study and the importance of study.

Chapter 2 reviews common types of process tomography systems, brief history of process tomography based mass flow rate measurement, flow velocity measurement techniques and embedded system technology.

Chapter 3 focuses on the hardware implementation of this research. The sensor configuration, signal conditioning circuits and architecture of the embedded systems are described.

Chapter 4 describes the software and firmware development to support the developed system. The data acquisition process, image reconstruction algorithm, cross correlation function, velocity profile measurement, mass flow rate measurement and communications between modules are explained thoroughly.

Chapter 5 presents the results obtained from experiments in terms of accuracy and processing speed. These results comprise of image reconstruction results, velocity measurement result and mass flow rate measurement results.

Chapter 6 states the conclusions made from this research and recommendations for future research.