MONITORING OF INDUSTRIAL PROCESS USING INTELLIGENT TOMOGRAPHY SYSTEM

By

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CERTIFICATION OF APPROVAL

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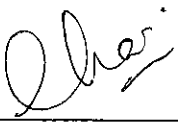
December 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.



Chai Yu Kiong

ABSTRACT

In any process industries, direct analysis of processes is very important for process control system implementation and improvement. To direct analysis on the processes, a real time process monitoring is required. Conventional methods of process monitoring system works by attached sensors inside the pipeline or vessel. Flow influence problem occurs when exist of sensor inside the pipeline. Solution for flow influence problem can be solved by using Electrical Process Tomography system. Electrical Process Tomography system using numbers of thin electrode plate as a sensor, and it is attached inner or outer surface of the pipeline (depend to the type of Tomography technique) to minimize the influence to the flow. This project with title "Monitoring of Industrial Process Using Intelligent Tomography System" will have objectives to study of Electrical Resistance Tomography (ERT) and develop a simple data acquisition system for ERT system. The outcomes of this project will be series of experiment results on practical of ERT technique and a working data acquisition system that able to records acquired data in a PC.

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LIST OF ABBREVIATIONS

ERT	Electrical Resistance Tomography
ECT	Electrical Capacitance Tomography
EMT	Electrical Inductance (Magnetic) Tomography
DAS	Data Acquisition System
VCCS	Voltage Controlled Current Source

CHAPTER 1
INTRODUCTION

1.1 Background of Electrical Process Tomography

In 1970s, numbers of application of Tomography imaging of process equipment have developed using Ionizing radiation from X-ray or isotope source, which is not satisfactory for the majority of process application on a routine basis because of the high cost and safety factor. In mid of 1980s a project on Electrical Capacitance Tomography began at Manchester for imaging multi-component flow from oil wells[1]. Around the same time medical scientist began realize the potential of Electrical Impedance Tomography as a safe, low cost method for imaging human body. At the same time, the development of low cost array processor did so much to solve the previous problems on high cost and slowness in image reconstruction. This has led to Electrical Process Tomography become a cost effective technique.

Electrical Process tomography is a technique of direct analysis of the internal characteristic of process plants. The main purpose of application of tomography in industry is to improve design and operation of equipment. Tomography system will come out with a real-time image that showing the cross section picture inside a vessel or pipeline. The information that can get from the images are flow regime, vector velocity, component concentration, fluid level etc.

Electrical Process Tomography involves the acquisition of measurement signals from sensors located on the periphery of an object, such as a process vessel or pipeline. This reveals information on the nature and distribution of components within the sensing zone. Most of the Tomography techniques are concerned with abstracting information to form a cross sectional image.

1.2 Problem Statement

The need of a direct analysis in process is very significant in many manufacturing industry. A direct analysis of the internal characteristic of the process inside the vessel or pipeline enables the engineer to analyze process control strategies and models developing. In order to have a direct analysis, a real time monitoring system is needed. Conventionally, most of the processes are monitored by putting a sensor for example flow sensor inside the pipelines to monitor the flow rate as required for analysis. In this case, the appearance of the sensor inside the pipeline indirectly will interrupt the flow regime and the flow speed inside the pipeline. This is an unwanted situation but normally it is difficult to avoid.

In order to fulfill the needs of direct process monitoring without breaking the basic rules, electrical tomography is the best solution since electrical tomography is not invasive. Electrical tomography provides two dimension image that can be used for few measurement and monitoring the process like flow regime, solid object detection, velocity profile and volumetric rate.

1.3 Objective & Project Scope

The objective of this project is to study the Electrical Resistance Tomography (ERT) and develop a simple data acquisition system for ERT system. The outcomes of this project will be series of experiment results on practical of ERT technique and a working data acquisition system that able to records acquired data in a PC.

CHAPTER 2
LITERATURE REVIEW

2.1 Electrical Process Tomography

In the industrial process monitoring, it is necessary for a monitoring system to monitor the real time parameter of the process. The industrial processes normally have very fast parameter change. To apply the tomography technology in industry process monitoring, it have to be fast enough to take a real time images. The method to rotate the sensor or object is physically impractical in the industry process monitoring. The time requires to rotate the assembly may take too long compare to changes occurring within the subject.

In the mid-1980s At University of Manchester there began a project on Electrical Capacitance Tomography for imaging multi-component flows from oil wells. That is a starting point of the Electrical Tomography in industrial process monitoring. Electrical Tomography is relatively fast, simple operation and has a strong construction and robust to cope with most industrial environments. The only disadvantage of Electrical Tomography is low spatial resolution (typically 3-10% of pipeline diameter) [1]. However this is sufficient for many practical industrial applications. There are three types of Electrical Tomography that had been developed. It is Electrical Capacitance Tomography (ECT), Electrical Resistance Tomography (ERT) and Electrical Inductance Tomography (EMT). Each Tomography use different technology and each of them have different purpose.

2.2 Electrical Resistance Tomography

An Electrical Resistance Tomography (ERT) system produces a cross-sectional two dimensional image showing the distribution of electrical conductivity of the contents of a process vessel from the measurements took from the periphery of the vessel. Figure 1 shows the basic component of the ERT system. Data acquisition system injects a current between a pair of electrodes and measures the resultant voltage difference between remaining electrode pairs according to a pre-defined measurement protocol (e.g. adjacent measurement strategy). The parameter sense by sensor will sent to image reconstruction unit. Image reconstruction unit collect enough data to produce a cross section image. Information can be abstracted from the cross section image. The image data can be analyzed quantitatively for subsequent use to improve process control or to develop models to describe individual processes.

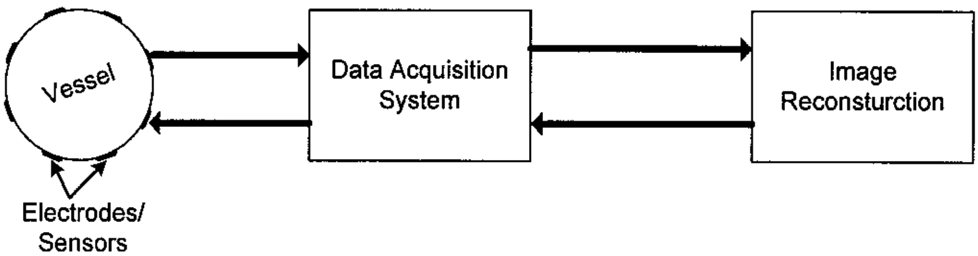


Figure 1 Typical ERT System

2.3 Sensor/Electrode

Generally the sensor that use in ERT is an electrode that connected to data acquisition system through co-axial cable. The purpose of coaxial cable used is to reduce the effect of extraneous environmental noise and interference [1]. The selection of material that used to make the electrode is depending on the process application. Typically, the material that used for electrode is brass, stainless steel, silver palladium alloy which is commercially available in bolt or crew form can often be threaded into the vessel wall. Electrode also can be coated at its tip with durable ceramic conductor, assuming any contact impedance within the electrode is small. The size of the electrode that contact with electrolyte is flexible as long as do not touch each other.

In electrode positioning, the electrode should be positioned at equal interval around the peripheral vessel in order to take the maximum amount of information from inside the vessel. In choosing the number of electrode (n) it must be noted that the time taken to acquire the data and reconstruction the image is a function of n, whereas the spatial resolution is proportional to $\sqrt{N}$ where N is the number of independent measurement [1].

2.4 Sensing Method

From the literature researches that have done on sensing method, most of the researcher use adjacent method as their ERT sensing system which shown in Figure 2. The other methods available are opposite method, multi-reference method, and multi-sink method. The methods other than adjacent and opposite method of injecting current require more current source/sink pair [1]. The adjacent and opposite protocol only require one current source and sink pair, there by minimizing the cost of the associated circuitry [1].

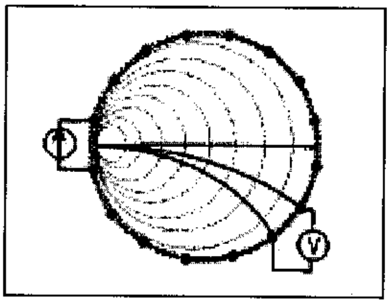


Figure 2 Adjacent Strategy

With N is number of electrodes, the adjacent measurement method takes N^2 measurements. However, there are only N(N-1)/2 measurements are independent. The current-injecting electrode is not measured to avoid electrode-electrolyte contact impedance problem. This is because of the voltage on the electrode carrying current are affected by the presence of electrical resistance between the electrode and the measurement object. Thus, the total of independent measurement is reduced to N(N-3)/2 [2].

From the Figure 2, current is applied between an adjacent pair of electrodes. The voltage difference between all the other adjacent pairs of electrodes is measured, excluding pairs for which one of the electrodes is carrying current. Current is them applied through the next pair of electrodes and the voltage measurement are repeated. This procedure is repeated for all pairs of neighboring electrodes until a full rotation of electrical field around the vessel have been made.

As we discuss before, the adjacent measurement method taking N^2 measurements. However, there are only N(N-1)/2 measurements are independent. The current-injecting electrode is not measured to avoid electrode-electrolyte contact impedance problem. Thus, the total of independent measurement is reduced to N(N-3)/2 [2].

Jun Wen and Feng Dong [3] had work on new sensing method by using single drive electrode method. Differing from adjacent method in which current injection and voltage measurement are running in pairs of electrodes, single drive electrode method complete the task in single electrode (Figure 3). In this method, every electrode except drive electrode is used to measure data point. With this method, the numbers of independent measurement is no longer N(N-3)/2. The total numbers of independent measurements is N(N-1)/2. With 16 electrodes in their experiment, there are 120 independent measurements. It is more than adjacent method which is only 104 data points [3].

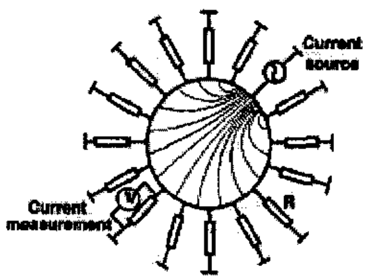


Figure 3 Single Drive Electrode Method [3]

By doing comparison on both methods, single drive method have more independent measurement data than adjacent method. The phenomena that data on the drive electrodes and the adjacent ones are not measured do not exist.

2.5 Sensing System

In the Tomography sensing system, some specifications need to follow to maintain the optimal flexibility and accuracy, whilst accommodating the majority of process application. The outline specification is as below [1]:

1. Injected a.c. current frequency bandwidth: 75 Hz to 153.6 kHz.
2. Injected a.c. current amplitude: 0-30 mA (peak to peak).
3. Methods of current injection: adjacent, opposite, multi-reference, and multi sink.
4. Analogue to digital converter (ADC) resolution: 12 bits minimum (about 0.025%).
5. Mode of measurement: either serial or parallel.
6. Maximum number of electrode modules: 32.

Thus it is necessary for a sensing system have the facility to either increase or decrease the amplitude of injected current in order to optimize the signal-to-noise ratio (SNR) of the measured voltage signal. For slow changing process, more accurate measurement is facilitated at lower frequencies of injection current [1].

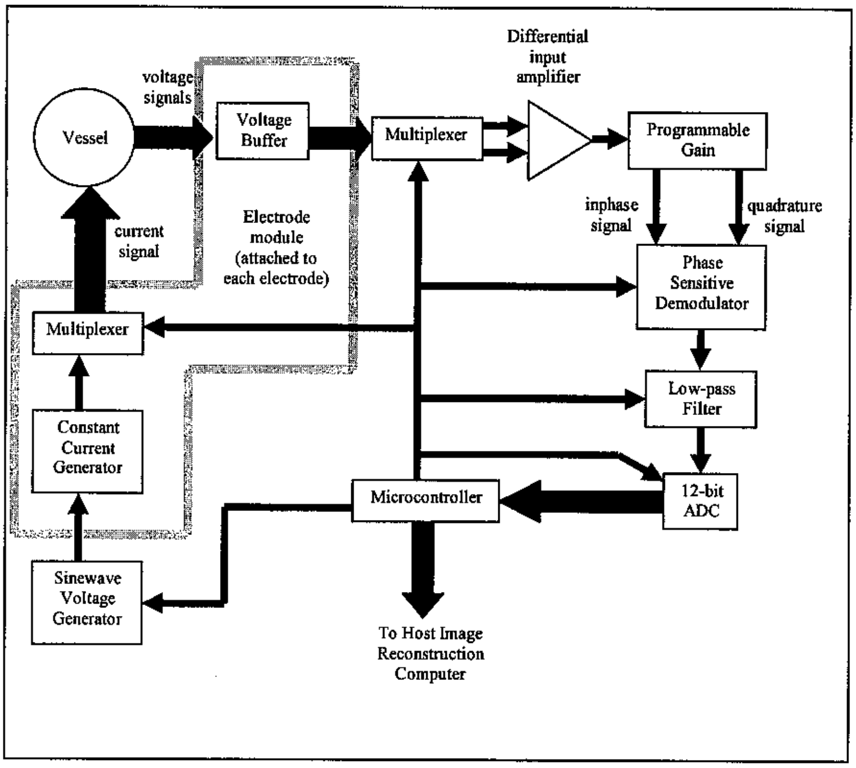


Figure 4 Component of a typical data acquisition system. Boxed components correspond to those contained in a small module attached to each individual sensing electrode [1].

Figure 4 shows the component in typical data acquisition system (DAS). Generally, the DAS has 3 basic parts. It is voltage generator, electrode module and voltage measurement demodulation and filtering function.

The sensing method discussed above is using sine wave AC current source to excite the electrodes. There is other method that using bi-directional current pulse to excite the electrodes. The measurement system that using this method is more simple compare to system using sine wave current source since demodulation and active low pass filter is not require. So high speed measurement can achieved [4].

2.6 Image Reconstruction

Computer is an essential part of any process tomography system. The data acquisition system is often under computer control, providing flexible and fast data capturing. The collected data are processed within the computer by using suitable image-reconstruction algorithm to generate cross-sectional images of the process media being studied. The realization of real time image reconstruction is usually dependent on the architecture and performance of the computer and the complexity of the algorithm.

There are several image reconstruction methods developed for ERT system. For example ridge-regression, eigenanalysis, perturbation method, Newton-Raphson method (non-linear iterative scheme), back-projection scheme, etc. In electrical Tomography, linear back-projection algorithm is the most used by engineer because it is very simple and computationally fast, due to the fact that the reconstruction process is reduced to matrix-vector multiplication [2].

In LBP reconstruction, reference voltages of each electrode pair are measured before any chances of conductivity [3]. These values will be the references to the changes of voltage when changes on conductivity of the subject occur.

The reconstruction algorithm for each pixel P(x,y) in tomogram is

$$P(x,y) = \frac{\sum_{m=1}^{M}\sum_{n=1}^{N} S_{m,n,x,y} \ln\left[\frac{V'(m,n)}{V(m,n)}\right]}{\sum_{m=1}^{M}\sum_{n=1}^{N} S_{m,n,x,y}} \qquad (1)$$

where,

m	= the current drive electrode pair.
n	= the voltage sense drive electrode pair.
V(m,n)	= the reference voltage measurement.
V'(m,n)	= the perturbed voltage measurement.
S	= the sensitivity coefficient.

The double sum of the denominator of equation (1) returns a natural number, which acts as a weight factor in situation when a given pixel belong to many sensitivity area. $S_{m,n,x,y}$ is taken as either 1 if pixel P(x,y) belongs to sensitivity area $A_{m,n}$ and 0 otherwise.

CHAPTER 3
METHODOLOGY

3.1 Project Planning

The methodology flow chart is shown Figure 5. The first technical task is sensor characteristic study and design since the sensor is the most fundamental part of this project. After complete of the sensor design, the next stage is sensing system design. The sensing system design will be include the sensing technique study, electronic circuit design and simulation on the sensing circuit. When the circuit is complete, PCB design and fabrication is needed. Project prototype design and fabrication will be the task after PCB design complete. After the project prototype complete, the ERT system testing will be running together with image reconstruction part. Image reconstruction part is the final part of this project. Any error detected will debug and system retests until all errors are eliminated. For this project, it is separated to two parts. First part will be complete in first semester and continue the second part in next semester. Every part of this project had been schedule accordingly as shown in Gantt chart at Appendix A.

3.2 Literature Research Work

After the Final Year Project title selection, the early research work is needed. The early literature research work includes the study and understanding the basic principle of this project, identify the project scope, identify the software/hardware required and the feasibility of this project. Reference book is the main resources of the research work at the beginning. The basic knowledge of the project can be achieved from the reference book. Apart of the books, dictionaries also used to understand some difficult term. The early research work of ERT system will be the source of ERT system design. This basic principle of ERT system include basic requirement of the sensor, technique that use in the sensing system, and also the image reconstruction.

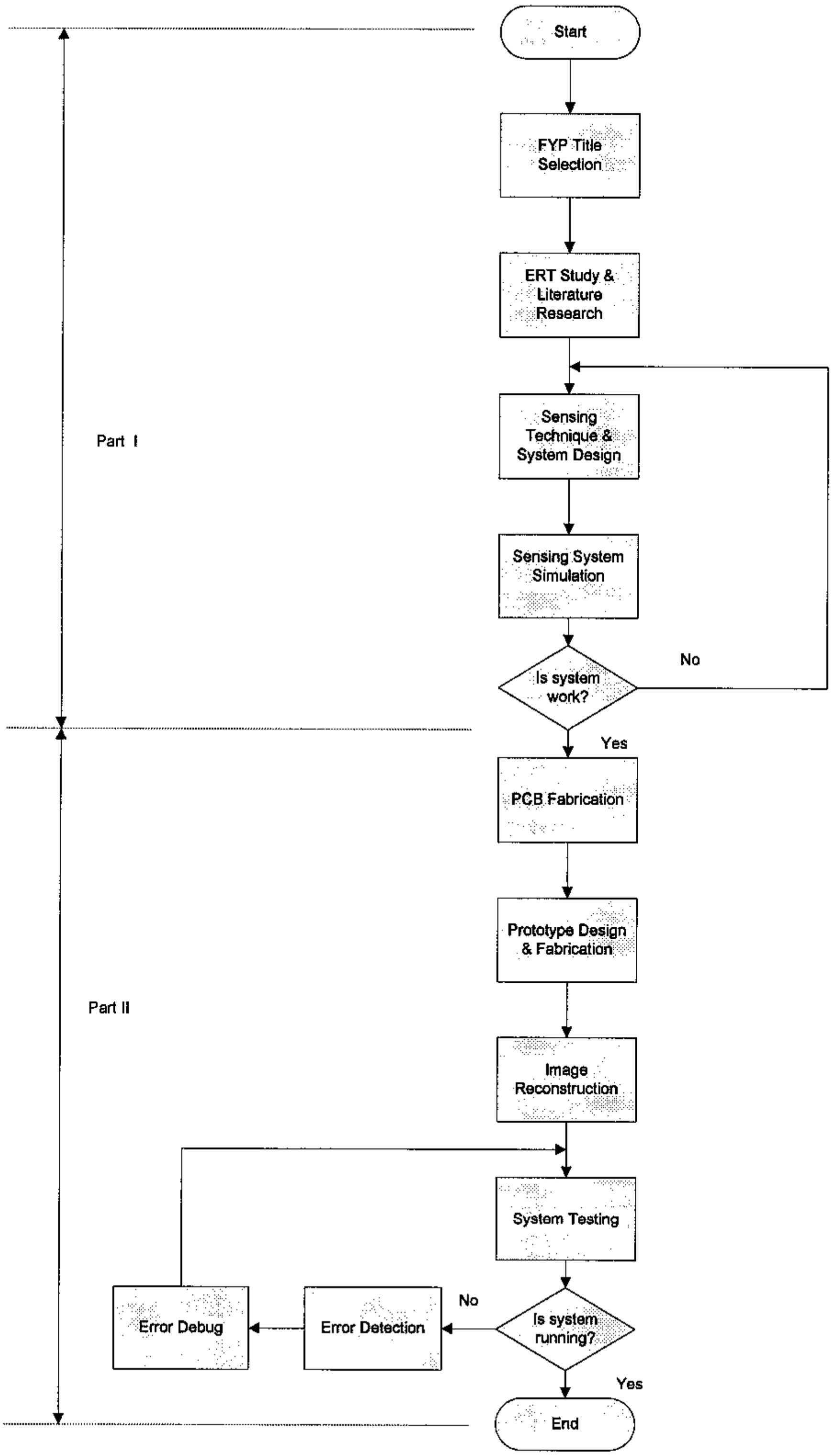


Figure 5 Project Flow Chart

After having the basic understanding of the ERT system, research will go further more on the study of latest research technical paper that publishes by some expert researcher. Some of the latest technology, technique, or result of ERT system will be obtained from the technical papers. The understanding of some important theory can be gained from reading the technical paper. From the latest information, some analysis can be done on the feasibility, availability, and applicability on this project. Some comparison also can be done on each different technique on the efficiency of the technique, and also feasibility of the technique to this project. Some problem in this project may be solved from the analysis that had been done before.

The literature research work will continue as project in progress. Some specific problem may need information from the research had been done by other expert researcher on the particular topic.

3.3 Study of Electrical Resistance Tomography

One of the objectives in this project is to study the Electrical Resistance Tomography. Other than doing literature research, few experiments had been done. The purpose to doing the experiment is to practically perform the ERT so that can understand more on the system.

3.3.1 ERT Lab Experiment 1

The first experiment done is to study the ERT result pattern of the measurement method using in ERT system. From literature research, measurement technique normally used in ERT is adjacent method as discussed in section 2.4. A constant current signal applied on a pair of electrode and voltage measured among the adjacent pairs of electrode. The constant current signal is produced by applied a sine wave to a simple voltage controlled current source (VCCS).

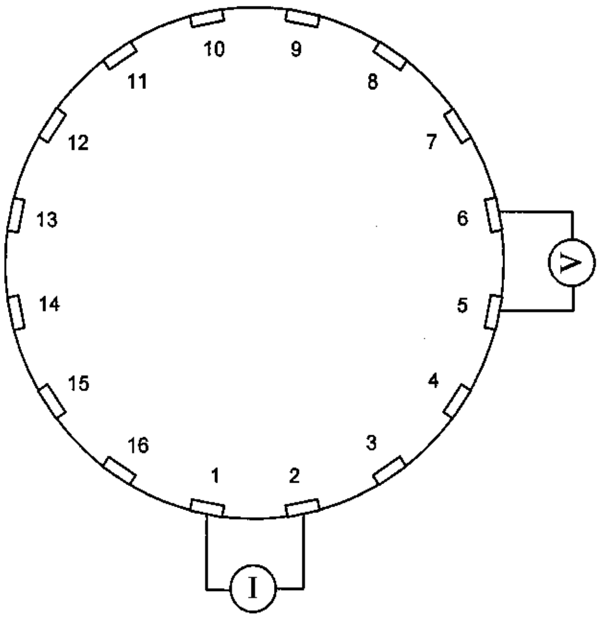


Figure 6 ERT Experiment 1 Setup

The setup of the experiment is shown in Figure 6. Sixteen Aluminium plates ware attached at the container wall as electrode. Output from VCCS applied on first electrode pair and voltage measured from adjacent electrode pair using digital multi-meter. The voltage ware recorded in worksheet and graph ware plotted and shown in section 4.1.

3.3.2 ERT Lab Experiment 2

Studies continue with doing experiment with putting a solid object inside vessel. The objective of this experiment is to study the difference of the results comparing to no object experiment results. The procedure of this experiment ware same with experiment discussed above. The different of this experiment is there are two reading needed for comparison. The first reading will be same with experiment previously discussed which no object put inside the vessel. This reading will be the reference experiment to next experiment.

After the first reading ware finished, solid object ware put at the middle of vessel. Then power supply turned on, voltage measured using digital multi-meter. All readings ware recorded accordingly. The results of two measurement ware plotted in same chart to compare the difference. Figure 7 shows the positioning of the solid object (cough syrup) inside the vessel.

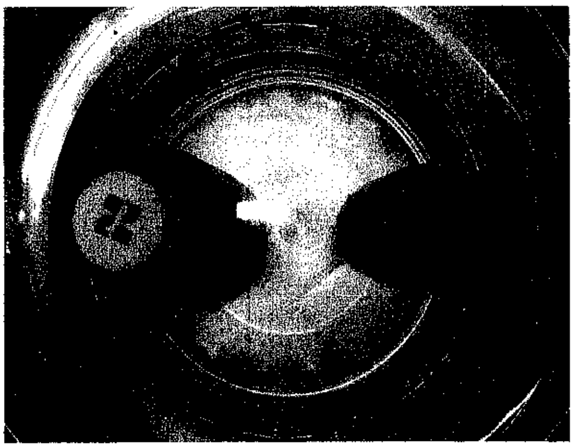


Figure 7 Position of Object Inside the Vessel

3.3.3 Image Reconstruction Studies

Image reconstruction is a process to develop a two or three dimensional image from the measurement results. There are many algorithms can be use for ERT image reconstruction for example, Newton-Rephson, Back-Projection, Ridge-regression etc. For real time ERT system, linear back projection algorithm is the most used by engineer because of its simplicity [2]. A complex algorithm will needs longer period to process data and will slow down the system. Normally a complex algorithm can produce a higher resolution image. In other word linear back projection only can produce a lower resolution, but the images produced will be sufficient for real time monitoring purposes. So resolution is not a big concern for real time monitoring.

3.3.3.1 Image Reconstruction Using Linear Back Projection Algorithm

In LBP reconstruction, reference voltages of each electrode pair are measured before any chances of conductivity. These values will be the references to the changes of voltage when changes on conductivity of the subject occur.

The reconstruction algorithm [2] for each pixel P(x,y) in tomogram is

$$P(x,y) = \frac{\sum_{m=1}^{M}\sum_{n=1}^{N} S_{m,n,x,y} \ln\left[\frac{V'(m,n)}{V(m,n)}\right]}{\sum_{m=1}^{M}\sum_{n=1}^{N} S_{m,n,x,y}} \tag{2}$$

where,

m	= the current drive electrode pair.
n	= the voltage sense drive electrode pair.
V(m,n)	= the reference voltage measurement.
V'(m,n)	= the perturbed voltage measurement.
S	= the sensitivity coefficient.

The double sum of the denominator of equation (2) returns a natural number, which acts as a weight factor in situation when a given pixel belong to many sensitivity area. $S_{m,n,x,y}$ is taken as either 1 if pixel P(x,y) belongs to sensitivity area $A_{m,n}$ and 0 otherwise.

$$S_{m,n,x,y} = \begin{cases} 1; & \text{if } P(x,y) \in A_{m,n} \\ 0; & \text{otherwise} \end{cases} \tag{3}$$

3.3.3.2 Sensitivity Coefficient Identification

From equation (3), the sensitivity coefficient $S_{m,n,x,y}$ is set to 1 if P(x,y) belongs to sensitivity area Am,n and 0 if otherwise. If pixel P(x,y) fall in the region "m" current drive electrode pair and "n" voltage sense electrode pair, $S_{m,n,x,y}$ is defined as 1. Otherwise if P(x,y) is outside of that region, $S_{m,n,x,y}$ will defined as 0. Sensitivity coefficient ware defined using graphical method.

The equal-potential is considered as straight line for this study. In real situation, the equal-potential lines are usually distorted by the regions of high conductivity [3]. Figure 8 shows the diagram to define sensitivity coefficient for current drive pair 1 and voltage sense pair 8, $S_{1,8,x,y}$.

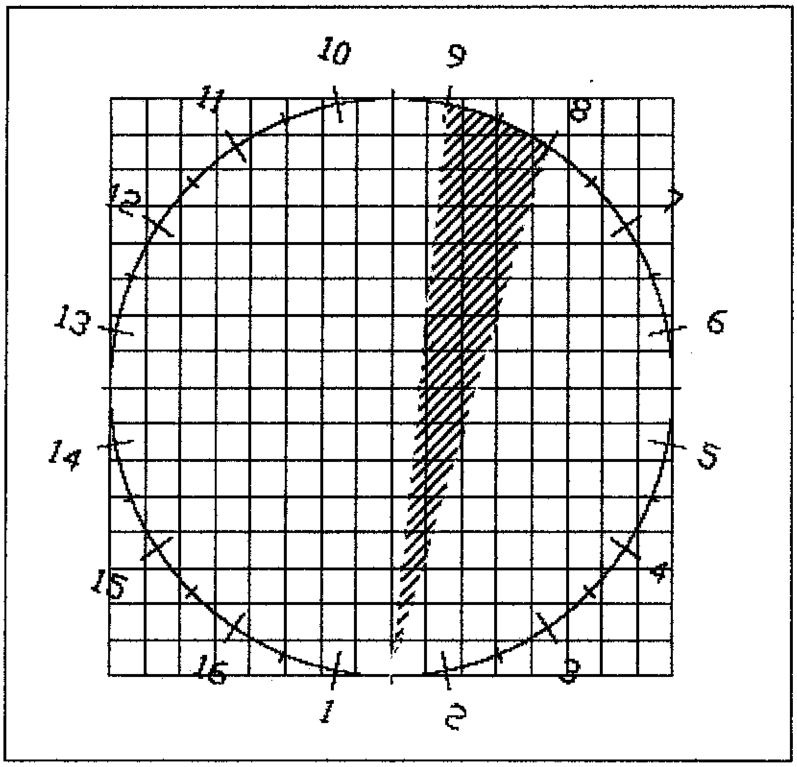


Figure 8 Sensitivity Coefficient Identification Diagram.

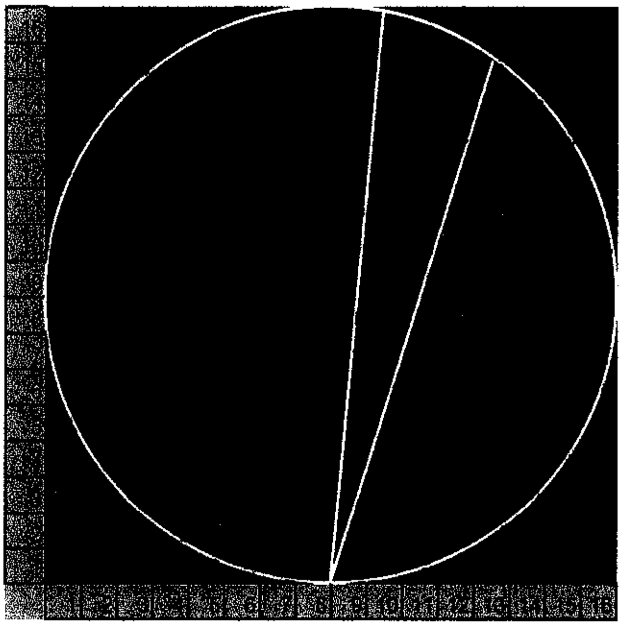


Figure 9 Identified Sensitivity Coefficient

From Figure 8, the region covered by yellow line is back-projected from current drive electrode pair 1 to voltage sense electrode pair 8. Which ever pixels are covered by the region will set to 1 for $S_{1,8,x,y}$. For the pixel that partially covered by the region, it is defined that at least ¼ of the pixel covered by the region will set to 1. In other hand, pixel that covered less than ¼, will not include in $S_{1,6,x,y}$. Figure 9 shows the defined coefficient for $S_{1,8,x,y}$. The complete coefficient table is recorded in Appendix B.

3.3.3.3 Image Development

By refer to equation (1), a tomographic image ware developed. Image development process is manually done using Microsoft Excel. Starting with the row data, natural value of perturbed voltage to reference voltage ratio ($ln(V_{perturbed}/V_{reference})$) are calculated. Then all the value are multiply with sensitivity coefficient $S_{m,n,x,y}$ for all x and y value. After that, each row of x,y value are summed. The total of each row of coefficient are calculated. Then the total value of natural value are divided with total of coefficient for each row of x,y to normalize the value to -1 to 1. After that, the final products of calculation are rearranged to matrix form. The matrix are imported to Matlab and plotted. The plotted image will be discussed in section 4 later.

3.4 Simple ERT Data Acquisition Design

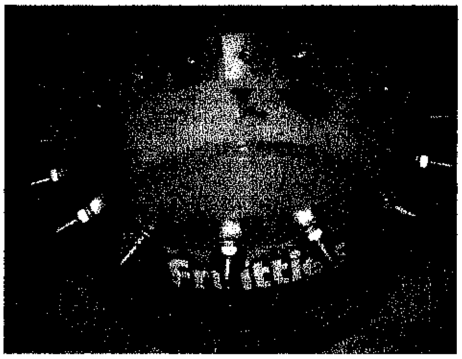
The second objective of this project is to design and implement a simple data acquisition system for ERT system. The scopes of this objective include signal generation, multiplexing, voltage measurement, central control unit design, and PC data recording.

3.4.1 Prototype Design

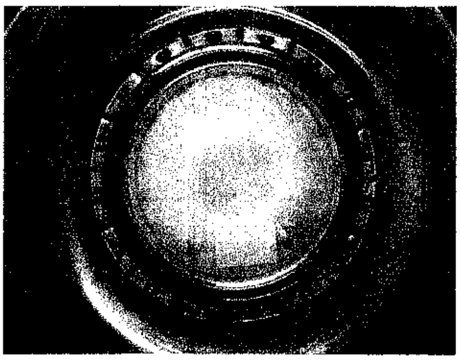
A prototype of a vessel attached with electrodes is designed and implemented. A container with diameter 12 cm and 18 cm in height is used as the vessel. Sixteen Aluminium plates are attached on the container wall using 1 cm screw. The prototype is shown in Figure 10. The specification of new design as below:

Specification	**Value**
Electrode size	2 cm x 2cm
Vessel diameter	12 cm
Gap between electrodes	≈ 3 mm

Table 1 Prototype Specification



(a) Side View



(b) Top View

Figure 10 ERT Prototype Design

In this design the screw head of this prototype are not flat with container wall surface. Although in real design the electrode plat should not extended from the surface, but due to this project does not deal with flow, so the extended screw head is not a concern. This project only design to detect any solid object inside the vessel. The screw head issue does not influence the performance of the results.

3.4.2 Constant Current Pulse Generation

To produce constant current signal, many methods available. Among the method common use is voltage controlled current source (VCCS). VCCS is using the configuration as shown in Figure 8. VCCS will produce a fixed output current with fixed input voltage.

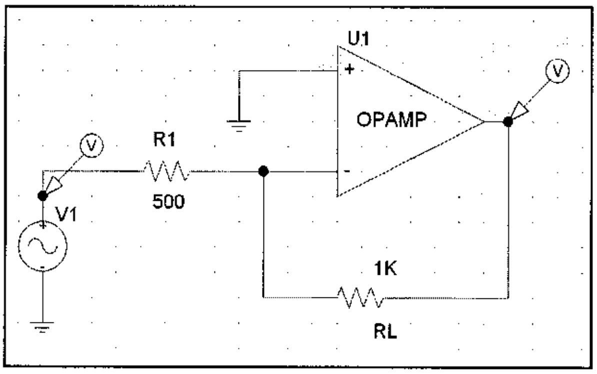


Figure 11 Voltage Controlled Current Source(VCCS)

The simulation on VCCS had been done using Pspice 9.1 student version. The design system will supply 10mA constant current. The configurations of VCCS are shown in Figure 11. The result of the simulation is shown in Table 4 and the design calculation is shown below:

Supply Current	: 10mA
Control voltage	: 5 Volt
Transconductance, gm	: 10mA/5V
	: 2mS
Therefore R1	: 1/gm
	: 1/2mS
	:500 ohm.

The load, RL resistance value using in this simulation is 100, 500, 1K, 2K and 2.5K. There is a limit on the load that use in this VCCS circuit. It is depend on the maximum output voltage of the op-amp. The maximum load can be calculated from the equation below. The maximum output voltage of the op-amp using in simulation is 15 volt. So the maximum load can calculated as below:

RL < R1(Vmax/Vi)

RL < 500(15V/5V)

< 1500 ohm

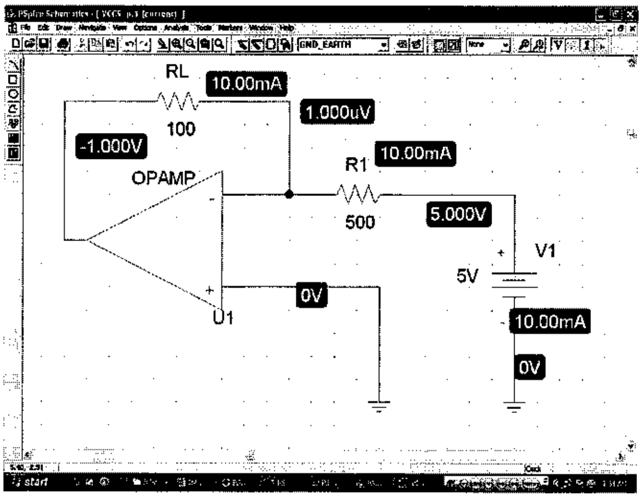


Figure 12   VCCS Simulation

There is another alternation of generate a bi-directional current pulse. It is using the CMOS switch network to alter the direction of the current from a constant current supply [4]. The design is shown in Figure 13. The operation of the circuit is shown in table 2. For positive cycle, switch S1 and S3 are closed and S2 and S4 opened. The current will flow through S1 to electrode A and back to source from electrode B through S3. At the negative cycle, switch S1, S3 opened, and S2, S4 closed. The current will flow to electrode B and back to source from electrode A through S2 and S4 respectively. The constant source is supply by a VCCS same as Figure 11, which is controlled by a constant input voltage.

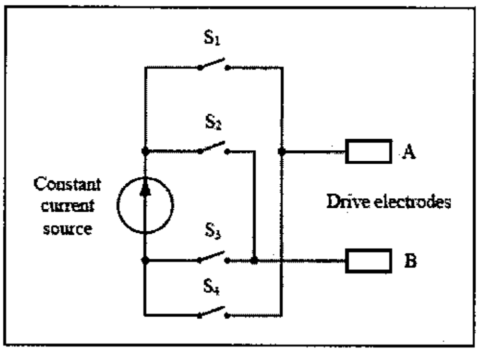


Figure 13   Bi-directional current pulse generation using switch method.

Table 2 Bi-directional current pulse generation circuit operation table

Cycle	S1	S2	S3	S4
Positive	Closed	Opened	Closed	Opened
Negative	Opened	Closed	Opened	Closed

3.4.3 Multiplexing

One of the interesting characteristic of Electrical Tomography is virtually rotating the sensor in order to "scan" the sensing area in order to explore entire cross section of the vessel. For adjacent sensing strategy, two electrodes are taken as current injection pair. The voltage difference between all other adjacent pair of electrodes is measured excluding pair for which one of electrode are carrying current. Current is then applied through the next pair of electrodes and voltage measurements are repeated. This procedure is repeated for all pairs of neighboring electrodes until a full rotation of electric field around the vessel cross section is obtained.

To electrically achieve the procedure above, four multiplexer with number of channel are equal or more than number of electrodes is needed. The multiplexer configuration is shown in Figure 14 and multiplexing strategy is shown in Appendix C.

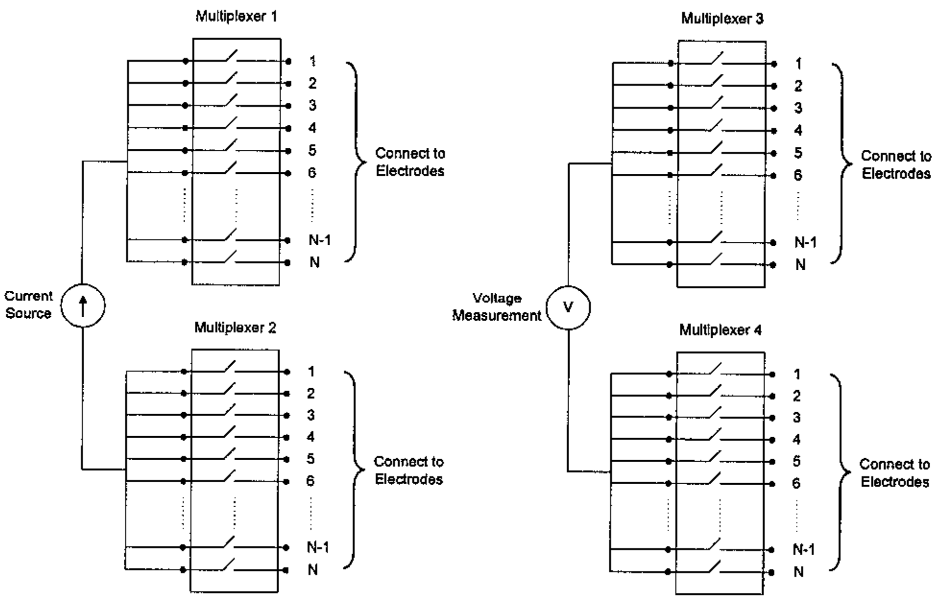


Figure 14 Multiplexer Configuration for Adjacent Method.

Figure 14 shows the connection of the multiplexer form the current source to electrodes and from electrode to voltage measurement circuit. The internal switch of the multiplexer will decide the signal goes to which electrode. All of the multiplexer will control by a microcontroller unit that will synchronize the switching time with other circuit system. Figure 15 shows the connection of the 16 channels multiplexer with 16 electrodes.

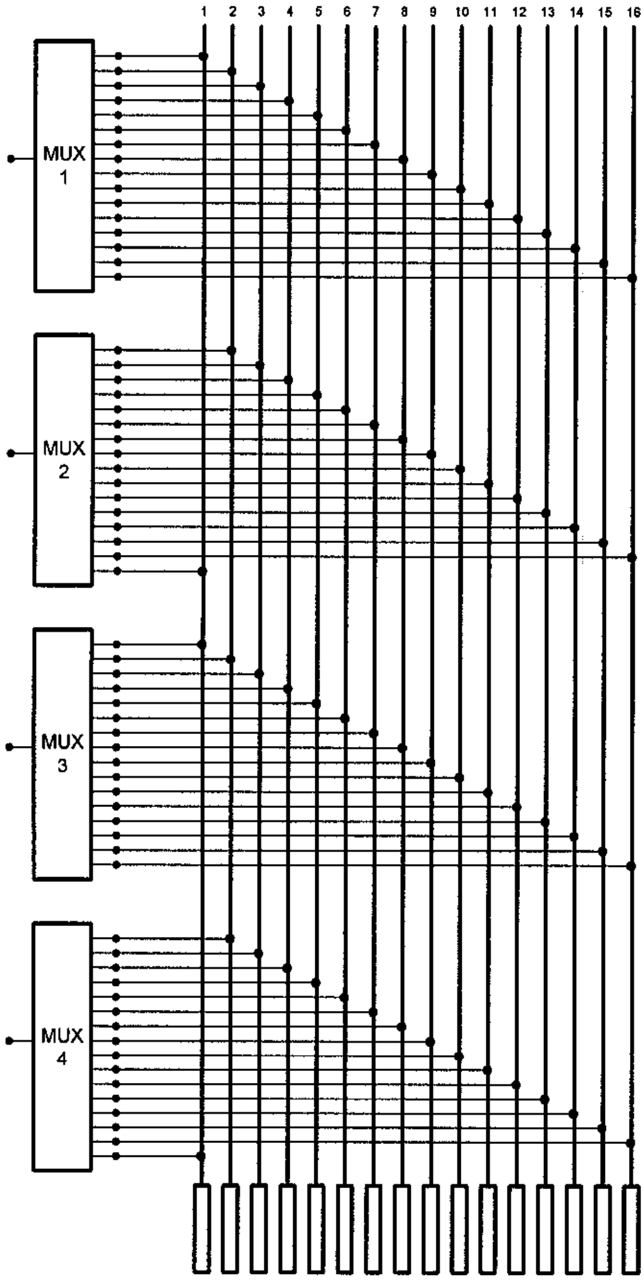


Figure 15 Connection diagram of four 16-channels multiplexers with 16 electrodes.

3.4.4 Multiplexer PCB Design

A PCB for multiplexing circuit had been designed using Eagle Layout Editor 4.13.

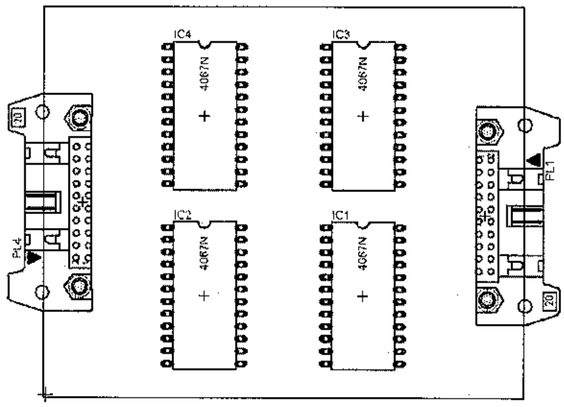


Figure 16 Component Layout of Multiplexing Circuit PCB Board.

The IDC connector of right hand side is designed to connect with electrodes. The connector at left hand side is an interface with control system and signals conditioning circuit.

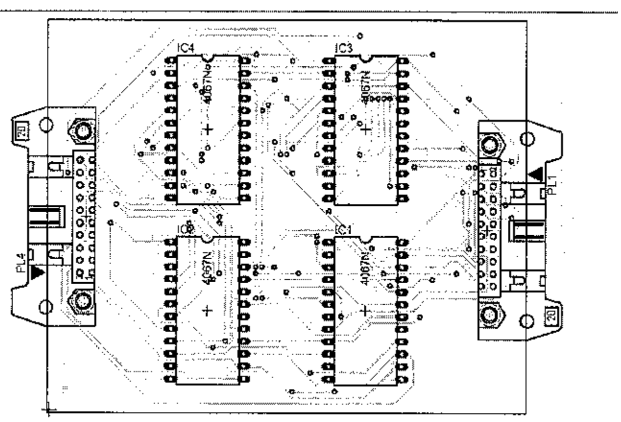


Figure 17 PCB layout with connection.

After PCB board of the multiplexer circuit is complete all components were attached and soldered on the PCB as shown in Figure 18:

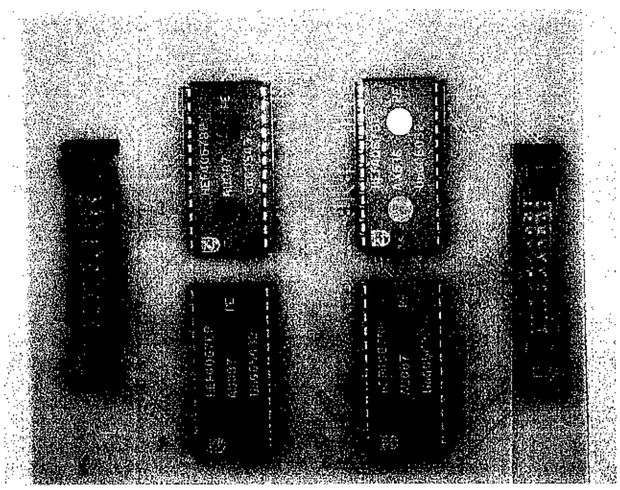


Figure 18 Multiplexer Printed Circuit Board.

3.4.5 Central Control Unit

Microcontroller is the central control unit of ERT data acquisition system. The main task of microcontroller in this system is to synchronize all the measurement process. This central control unit has five major functions. It is signal generation, signal injection & voltage measurement switching, sample & hold, analog to digital conversion and PC interface as shown in Figure 19. Microcontroller that used in this project is 16F877 from Microchip.

PIC 16F877 used in this project because of its internal features and the number of input/output available. PIC 16F877 have 8K word (14bit) program memory, 368 bytes of RAM space and 256 bytes of EEPROM space. It also have few build-in feature like 8/16 bit timers, 2 capture and compare PWM modules, 10 bit multi channel ADC and built-in USART (Universal Synchronous/Asynchronous Receiver Transmitter). Programming code of central control unit shown in Appendix D.

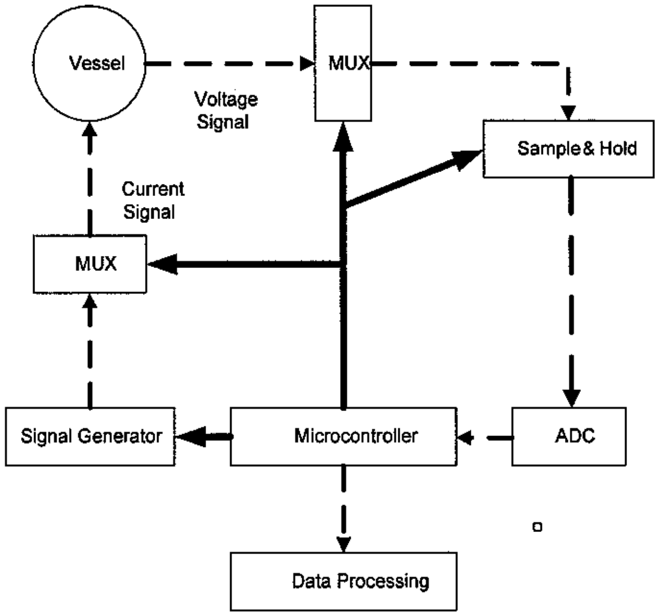


Figure 19 Central Control Unit.

3.4.5.1 Signal Generation

As discussed in section 3.5.1, the source of signal is a constant current provide by a voltage controlled current source (VCCS). Before the constant current signal source to multiplexing circuit, it goes through a set of CMOS switches. The CMOS switches will convert the DC current source to bi-directional current signal by switching technique. Control input of CMOS switch is controlled two microcontroller output. The connection of microcontroller to VCCS are shown in Figure 20. Table 3 shows the switching sequence and Figure 21 is the timing diagram of signal generation switching.

Table 3 Bi-directional current pulse generation circuit operation table

Cycle	S1	S2	S3	S4
Positive	Closed	Opened	Closed	Opened
Negative	Opened	Closed	Opened	Closed

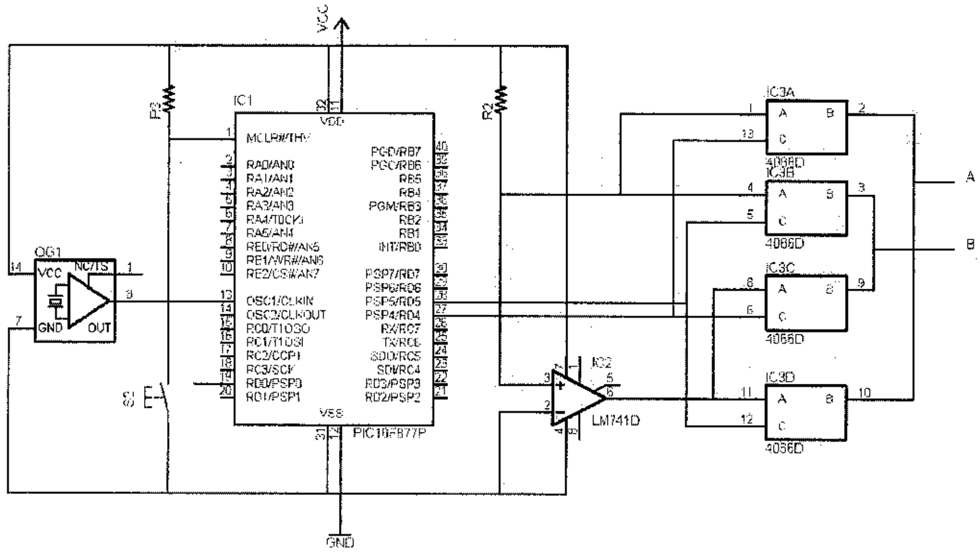


Figure 20 Bidirectional Current Signal Generation

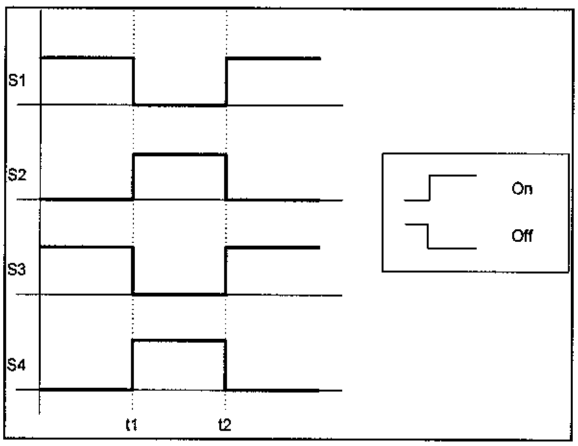


Figure 21 Timing diagram for signal generation switching.

3.4.5.2 Multiplexer Switching

Multiplexers are used for switching the signal injection and voltage measurement pair of electrodes. To meet the adjacent measurement sequences, central control unit will provides series of switching addresses to multiplexer. The switching sequences of adjacent measurement method are shown in Appendix C. Port C and Port D of PIC 16F877 used for multiplexer addressing for signal injection and voltage measurement respectively. The output of each port is a 4 bit address from 0000 to 1111 to control 16 internal CMOS switch of multiplexer. The multiplexing schematic circuit shown in Figure 22. The figure only shows the connection of microcontroller output to multiplexer addressing input. The connection of multiplexer to electrode shown in Figure 15.

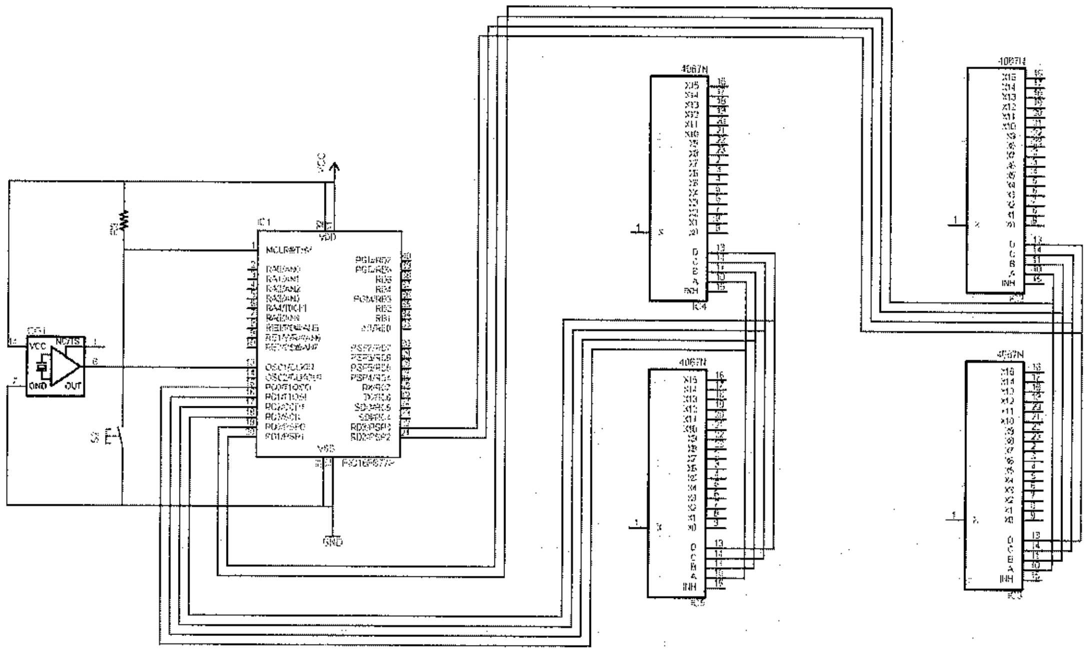


Figure 22 Multiplexer Addressing Schematic

3.4.5.3 Analog to Digital Conversion

The voltages measured at electrodes will send to analog input of microcontroller. There is build-in analog to digital converter in PIC16F877. For PIC16F877, port A are special build for analog input. Pin RA0 to RA7 can all use for multiple analog input or single analog input. If specific full scale voltage used for ADC, the voltage value need to apply to pin RA3. For this project, the maximum value of voltage value is around 500 mV. So 1 volt reference voltage applied to pin RA3 as full scale value. The ADC used in this project is 10bits ADC. The input voltage will converted by using formula below:

$$X = \frac{Vin}{Vfullscale} x\left(2^{n} - 1\right) \qquad (4)$$

Which X is converted value, n is number of bit in ADC. Since n = 10bits, $V_{fullscale}$ = 1 volt, the formula are simplify as below:

$$X = \frac{Vin}{1Volt} x(1023) \tag{5}$$

In this situation, the resolution of this ADC design is

$$V_{resolution} = \frac{V_{fullscale}}{2^n - 1} = \frac{1volt}{1023} = 9.775x10^{-4} V$$

Before the converted value transfer to data recorder, the converted value need to convert back to original value so that value accepted at data recorder is the actual value of input. Input value can convert back by using formula below:

$$V_{in} = XxV_{resolution} = Xx9.775x10^{-4} V \tag{6}$$

3.4.5.4 PC Interface & Data Transfer

After converted to digital data, the data sent to data recorder system which is a personal computer. In PIC16F877, the USART (Universal Synchronous/Asynchronous Receiver Transmitter) is utilized for asynchronous serial communication. The most common protocol used for asynchronous communication in microcontroller is the RS232 protocol. The PIC16F877 does not transmit the signals at RS232 directly but does it through a driver such as MAX232. Pin RC6 and RC7 of port C are special designed by Microchip as data receive and transmit purpose. The schematic diagram of data communication shown in Figure 23.

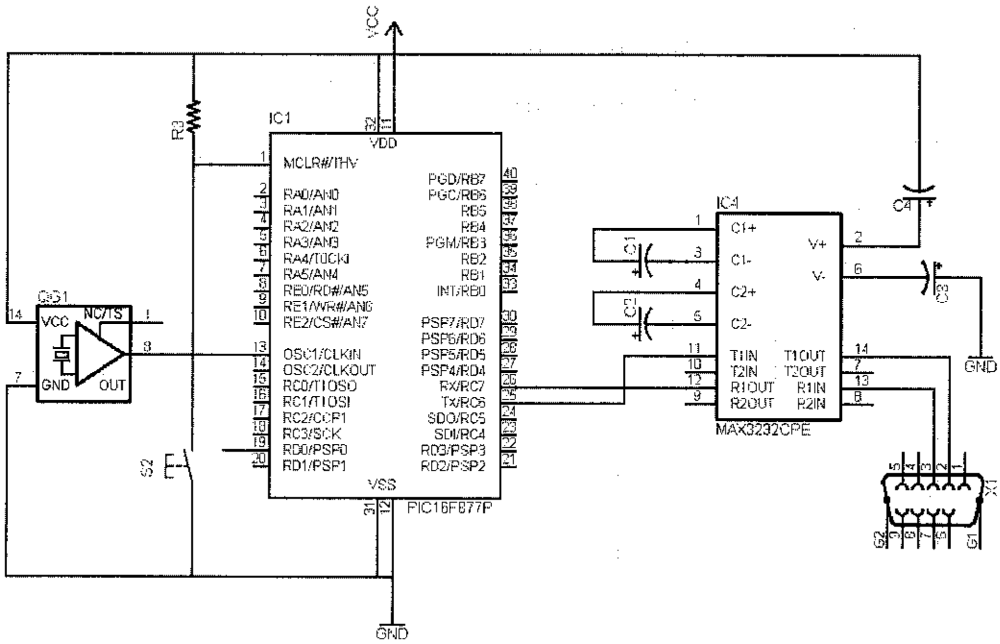


Figure 23 PC Interface Schematic Diagram

3.4.6 Data Recording

The voltage signal measured from vessel are converted to digital signal by analog to signal conversion that done in central control unit. The converted signal will send to computer through serial communication port RS232. Data recorder will record the received data into text file through Hyper Terminal. The recorded data will be used for image reconstruction. The configuration at Hyper Terminal must set to the same configuration at microcontroller. The setting must be set is baud rate, parity and bit.

CHAPTER 4
RESULTS & DISCUSSION

4.1 ERT Experiment 1 Result

Table 1 is the result of the first ERT experiment. The objective of this experiment is to study the result pattern of adjacent measurement methods. The number of electrode used in this experiment is sixteen electrodes. According to adjacent method, current signal applied on the first pair of electrode and voltage measured all other adjacent pairs of electrode excluding pairs for which one of the electrodes is an electrode carrying current. So number of voltage measurement is thirteen measurements.

Table 4 ERT Lab Experiment Results

Measurement	Voltage (mV)
1	239.11
2	74.82
3	40.22
4	20.99
5	17.03
6	13.26
7	12.95
8	14.32
9	15.88
10	24.52
11	38.00
12	75.68
13	263.45

From the result in table 4, a graph is plotted as shown in Figure 24. Refer to Figure 24, voltage is higher at the first measurement. Voltage is decrease from first measurement to measurement six. Then voltage starts climbing back from measurement eight to measurement thirteen. By refer back to Figure 6 in section 3.3.1, we can observed that voltage is highest at electrode pair closest to current carrying pair. Voltage decrease when electrode pair away from current injection electrode pair. Voltage is lowest at electrode pair which has longest distance from current injection pair.

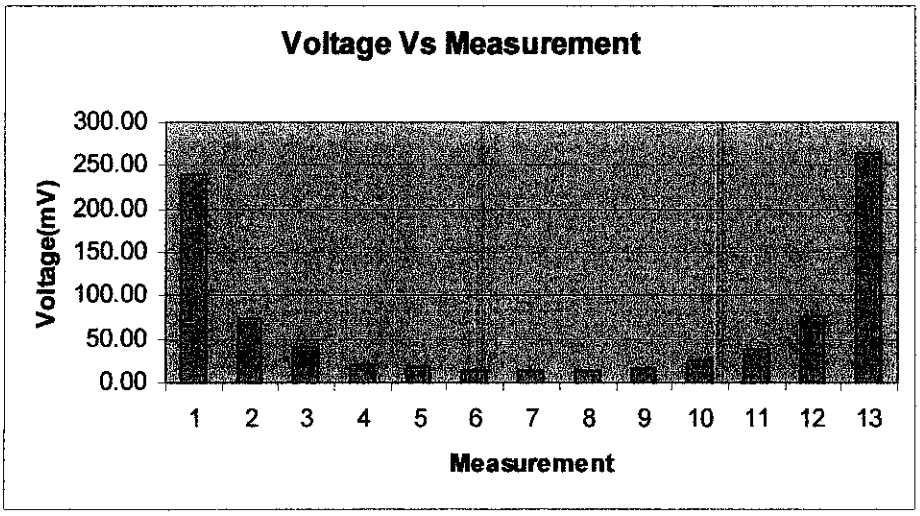


Figure 24 Result pattern of ERT experiment 1

4.2 ERT Lab Experiment 2

The purpose of this ERT experiment 2 is to evaluate effect of an object exist inside the medium in ERT system. From Figure 25, we can see that every excitation will produced voltage with higher value for electrode pairs which closer to excitation electrode and lower value for electrode farther from excitation pair. From the plotted graph below, graph in pink color is perturbed voltage and graph in blue color is reference voltage. The graph shows the perturbed voltage have significant different from reference voltage for certain measurement. This indicates the effect of object on the results. Figure 26 shows the difference of the measured value among two experiments.

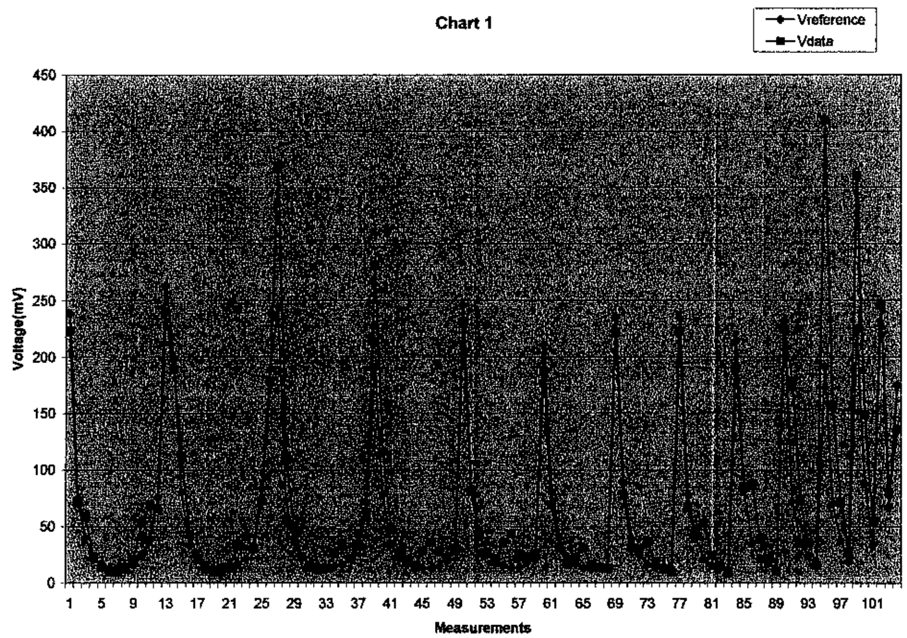


Figure 25 ERT voltage measurement

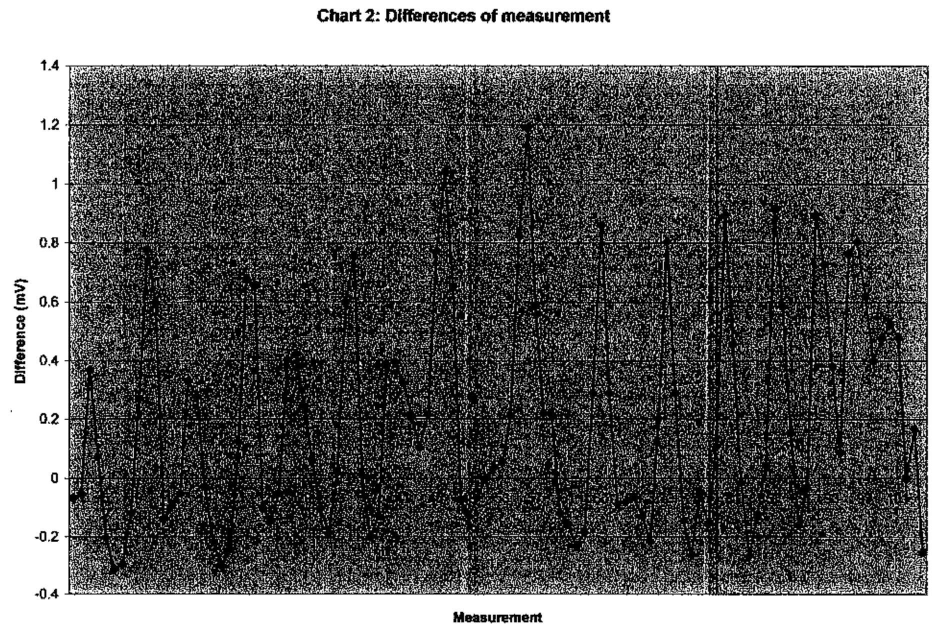


Figure 26 Difference of two measurement

4.3 Image Reconstruction

Figure 27 shows the plotted image which is a tomograpic image. According to the scale of the image, the color change from dark blue to red proportional with the value change from 0 to 1. From the image, portion of the pixels at centre are in yellow color which mean that the value at the centre are higher. Two objects inside the vessel can visually identify from the image.

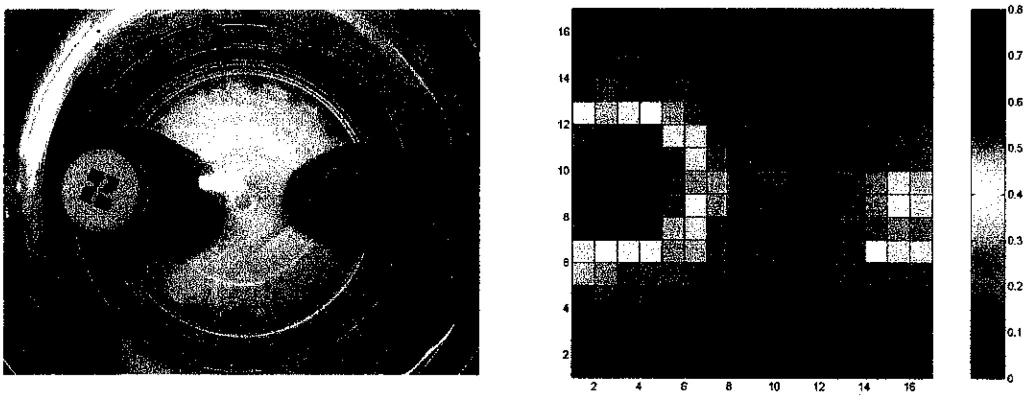


Figure 27 Developed Image Compare to Experiment Setup

4.4 Voltage Controlled Current Source Simulation Results

The results of VCCS simulation are shown in Table 5 below:

Table 5 Results of VCCS Simulation

RL (ohm)	I_{RL} (mA)	Vout (V)
100	10	5
500	10	10
1K	10	15
1.5K	10	15
2K	8	15
2.5k	6.667	15

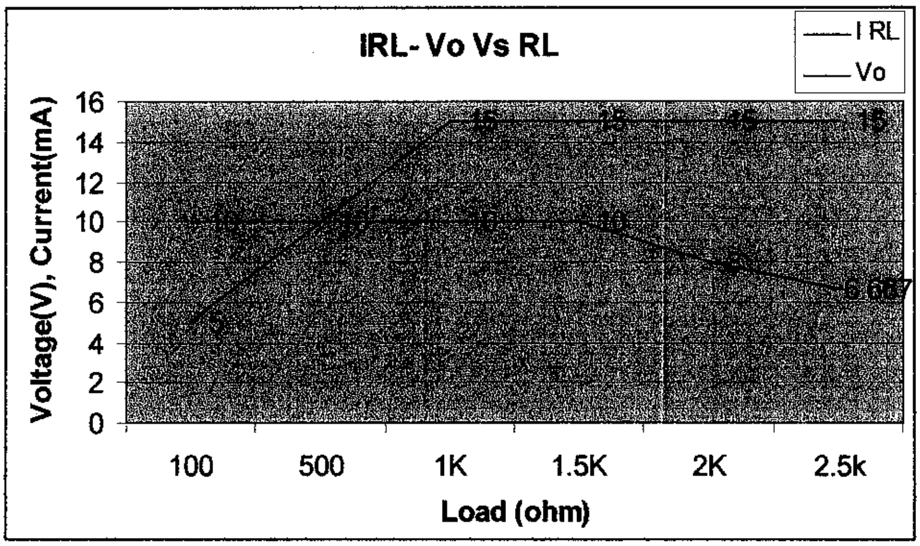


Figure 28 Output Current & Output Voltage Vs Load Resistance

From the chart in Figure 28, we can observed that the output current maintain in 10 mA from beginning until load 1.5 Kohm. The output voltage increase from beginning until it reaches maximum output voltage 15 Volt. The output voltage keep in constant even load increases. The output current start decrease after op-amp reaches it maximum output voltage. In conclusion, the maximum load allowed to apply in this design is 1.5 K ohm. This design have low maximum output load.

4.5 Multiplexer Performance Test

A performance test had been conducted for the multiplexer. The 4-bit binary counter is connected to the modified multiplexer PCB board to control the switching of the multiplexer. A sine wave signal from function generator is connected to the input of the multiplexer. The setup of the test is shown in Figure 29. The output of every channel of the multiplexer ware tested using an oscilloscope. The input and output wave form is compared. Figure 30 shows the results of the output of activated channel through oscilloscope.

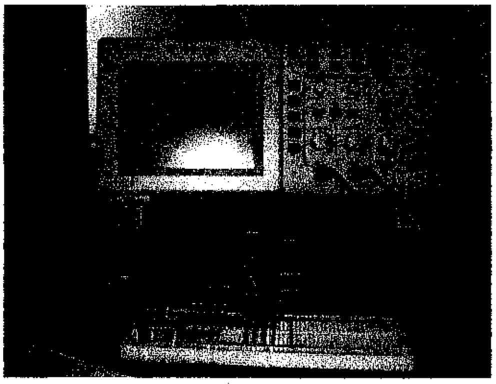
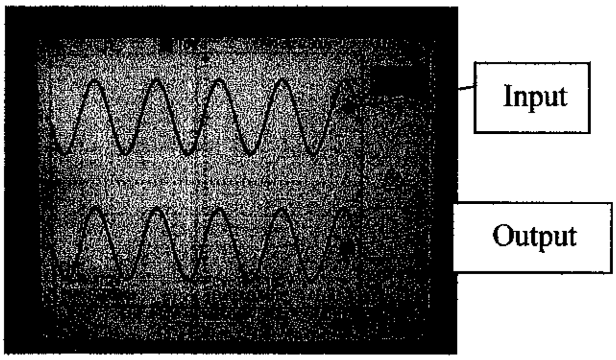
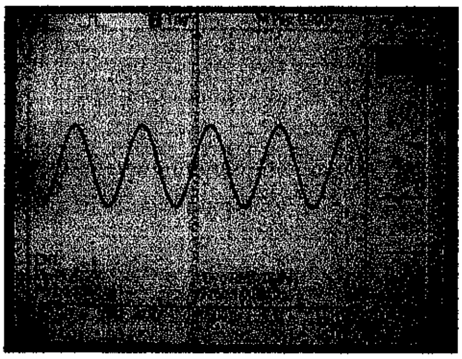


Figure 29 Setup of multiplexer performance test.



(a) Input signal compare and output signal



(b) Comparison of two signals.

Figure 30 Result of the activated multiplexer channel.

From the results, the shape of the output signal is same with input signal. When two signals ware put at same axis as shown in Figure 30 (b), it shows that the amplitude and phase of the input output signal is same. Figure 31 shows the input output signal of the non-activated channel. Some unexpected result occurs on the output signal.

Theoretically, the output signal should be zero. The occurrence of this signal at the non-activated will cause interference to activated signal and bring to not accuracy on reading.

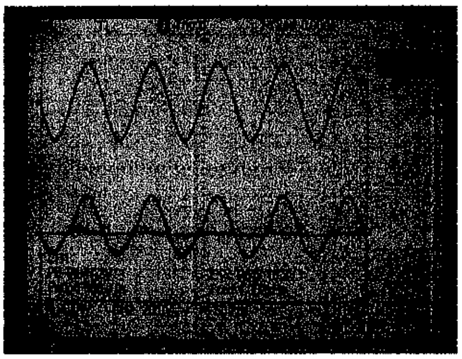


Figure 31 Result of Non-Activated Multiplexer Channels.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 Conclusion

Experimental studies had been done on Electrical Resistance Tomgoraphy. Results from experiment show the difference of reference voltage and perturbed voltage. Image reconstructed from experiment results. An image of 16 x 16 in pixel is reconstructed using linear back projection algorithm. The developed image shows the difference reading at the region which solid object located with different color.

A simple data acquisition is successful developed. The system is designed to acquire data using adjacent method. All measured data are recoded in computer. In this system, the voltage ware directly source to analog to digital converter input. This will cause the error to reading when there is noise occur on the signal. It is suggested to improve the system by using signal condition circuit. Signal conditioning circuit may able to filter out all noise occur. Figure 32 shows the complete ERT system.

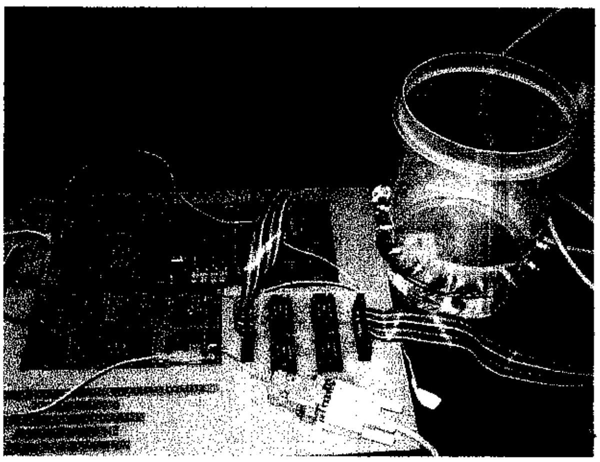


Figure 32 Complete ERT System

Reference:

[1] R E Williams and M S Beck, "Process Tomography-Principles, Techniques and Application", Butterworth-Heinemann, 1995.

[2] Quak Foo Lee, Advanced Chemical Technology Centre, "Electrical Resistance Tomography (ERT)", 2nd Jan 2006, http://www.chmltech.com/tomography.htm.

[3] Jun-Wen Liu and Feng Dong, "Electrical Resistance Tomography Based On The Single Drive Electrode Method", IEEE Transactions on Machine Learning and Cybernetics, Vol. 1, pp632-637, Aug. 2004.

[4] ZHU Jian-Ping, WANG Bao-Liang, Huang Zhi –Yao, LI Hai-Qing, "Design of ERT System", Journal of Zhejiang University SCIENCE, 6A(12):1446-1448, Sept. 2005

APPENDIX A

Milestone for the First Semester of 2 Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Selection of Project Topic																	
2	Preliminary Research Work																	
3	Submission of Preliminary Report				●													
4	Project Work																	
	- Data acquisition & processing study																	
	- Sensing system design I																	
5	Submission of Progress Report									●								
6	Project work continue																	
	- Sensing system design II																	
	- Sensing system simulation																	
7	Submission of Interim Report Final Draft													●				
8	Submission of Interim Report															●		
9	Oral Presentation																●	

Milestone for the Second Semester of 2 Semester Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Work Continue														
	- PCB Design														
	- PCB fabrication														
2	Submission of Progress Report 1			●											
3	Project Work Continue														
	- ERT prototype design														
	- ERT prototype fabrication														
4	Submission of Progress Report 2								●						
5	Project work continue														
	- Image reconstruction simulation														
	- ERT system testing & modification														
6	Submission of Dissertation Final Draft												●		
7	Oral Presentation													●	
8	Submission of Project Dissertation														●

APPENDIX B

LBP SENSITIVITY COEFFICIENT TABLE

Inject		1													2													3												4										
		2													3													4												5										
Measure		3	4	5	6	7	8	9	10	11	12	13	14	15	4	5	6	7	8	9	10	11	12	13	14	15	16	5	6	7	8	9	10	11	12	13	14	15	16	6	7	8	9	10	11	12	13	14	15	16
		4	5	6	7	8	9	10	11	12	13	14	15	16	5	6	7	8	9	10	11	12	13	14	15	16	1	6	7	8	9	10	11	12	13	14	15	16	1	7	8	9	10	11	12	13	14	15	16	1
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Inject		1												
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Inject		2												
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Measure		4	5	6	7	8	9	10	11	12	13	14	15	16
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	16													

Inject		3											
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Inject		5										6									7								8							9						10					11				12			13		14
		6										7									8								9							10						11					12				13			14		15
Measure		7	8	9	10	11	12	13	14	15	16	8	9	10	11	12	13	14	15	16	9	10	11	12	13	14	15	16	10	11	12	13	14	15	16	11	12	13	14	15	16	12	13	14	15	16	13	14	15	16	14	15	16	15	16	16
		8	9	10	11	12	13	14	15	16	1	9	10	11	12	13	14	15	16	1	10	11	12	13	14	15	16	1	11	12	13	14	15	16	1	12	13	14	15	16	1	13	14	15	16	1	14	15	16	1	15	16	1	16	1	1
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Measure		7	8	9	10	11	12	13	14	15	16	8	9	10	11	12	13	14	15	16	9	10	11	12	13	14	15	16	10	11	12	13	14	15	16	11	12	13	14	15	16	12	13	14	15	16	13	14	15	16	14	15	16	15	16	16
		8	9	10	11	12	13	14	15	16	1	9	10	11	12	13	14	15	16	1	10	11	12	13	14	15	16	1	11	12	13	14	15	16	1	12	13	14	15	16	1	13	14	15	16	1	14	15	16	1	15	16	1	16	1	1
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APPENDIX C

MULTIPLEXING STRATEGY

Table below shows active channel of every multiplexer for each sequence.

	MUX Pair		Current Injection		Voltage Measurement		Truth Table							
Seq	Inject	Measure	MUX 1	MUX 2	MUX 3	MUX 4	MUX 1 & 2				MUX 3 & 4			
1		3			3	4					0	0	1	0
2		4			4	5					0	0	1	1
3		5			5	6					0	1	0	0
4		6			6	7					0	1	0	1
5		7			7	8					0	1	1	0
6		8			8	9					0	1	1	1
7	1	9	1	2	9	10	0	0	0	0	1	0	0	0
8		10			10	11					1	0	0	1
9		11			11	12					1	0	1	0
10		12			12	13					1	0	1	1
11		13			13	14					1	1	0	0
12		14			14	15					1	1	0	1
13		15			15	16					1	1	1	0
14		4			4	5					0	0	1	1
15		5			5	6					0	1	0	0
16		6			6	7					0	1	0	1
17		7			7	8					0	1	1	0
18		8			8	9					0	1	1	1
19		9			9	10					1	0	0	0
20	2	10	2	3	10	11	0	0	0	1	1	0	0	1
21		11			11	12					1	0	1	0
22		12			12	13					1	0	1	1
23		13			13	14					1	1	0	0
24		14			14	15					1	1	0	1
25		15			15	16					1	1	1	0
26		16			16	1					1	1	1	1
27		5			5	6					0	1	0	0
28		6			6	7					0	1	0	1
29		7			7	8					0	1	1	0
30		8			8	9					0	1	1	1
31		9			9	10					1	0	0	0
32	3	10	3	4	10	11	0	0	1	0	1	0	0	1
33		11			11	12					1	0	1	0
34		12			12	13					1	0	1	1
35		13			13	14					1	1	0	0
36		14			14	15					1	1	0	1
37		15			15	16					1	1	1	0
38		16			16	1					1	1	1	1

39	4	6	4	5	6	7	0	0	1	1	0	1	0	1
40		7			7	8					0	1	1	0
41		8			8	9					0	1	1	1
42		9			9	10					1	0	0	0
43		10			10	11					1	0	0	1
44		11			11	12					1	0	1	0
45		12			12	13					1	0	1	1
46		13			13	14					1	1	0	0
47		14			14	15					1	1	0	1
48		15			15	16					1	1	1	0
49		16			16	1					1	1	1	1
50	5	7	5	6	7	8	0	1	0	0	0	1	1	0
51		8			8	9					0	1	1	1
52		9			9	10					1	0	0	0
53		10			10	11					1	0	0	1
54		11			11	12					1	0	1	0
55		12			12	13					1	0	1	1
56		13			13	14					1	1	0	0
57		14			14	15					1	1	0	1
58		15			15	16					1	1	1	0
59		16			16	1					1	1	1	1
60	6	8	6	7	8	9	0	1	0	1	0	1	1	1
61		9			9	10					1	0	0	0
62		10			10	11					1	0	0	1
63		11			11	12					1	0	1	0
64		12			12	13					1	0	1	1
65		13			13	14					1	1	0	0
66		14			14	15					1	1	0	1
67		15			15	16					1	1	1	0
68		16			16	1					1	1	1	1
69	7	9	7	8	9	10	0	1	1	0	1	0	0	0
70		10			10	11					1	0	0	1
71		11			11	12					1	0	1	0
72		12			12	13					1	0	1	1
73		13			13	14					1	1	0	0
74		14			14	15					1	1	0	1
75		15			15	16					1	1	1	0
76		16			16	1					1	1	1	1
77	8	10	8	9	10	11	0	1	1	1	1	0	0	1
78		11			11	12					1	0	1	0
79		12			12	13					1	0	1	1
80		13			13	14					1	1	0	0
81		14			14	15					1	1	0	1
82		15			15	16					1	1	1	0
83		16			16	1					1	1	1	1

84	9	11	9	10	11	12	1	0	0	0	1	0	1	0
85		12			12	13					1	0	1	1
86		13			13	14					1	1	0	0
87		14			14	15					1	1	0	1
88		15			15	16					1	1	1	0
89		16			16	1					1	1	1	1
90	10	12	10	11	12	13	1	0	0	1	1	0	1	1
91		13			13	14					1	1	0	0
92		14			14	15					1	1	0	1
93		15			15	16					1	1	1	0
94		16			16	1					1	1	1	1
95	11	13	11	12	13	14	1	0	1	0	1	1	0	0
96		14			14	15					1	1	0	1
97		15			15	16					1	1	1	0
98		16			16	1					1	1	1	1
99	12	14	12	13	14	15	1	0	1	1	1	1	0	1
100		15			15	16					1	1	1	0
101		16			16	1					1	1	1	1
102	13	15	13	14	15	16	1	1	0	0	1	1	1	0
103		16			16	1					1	1	1	1
104	14	16	14	15	16	1	1	1	0	1	1	1	1	1

APPENDIX D

CENTRAL CONTROL UNIT PROGRAM CODE

```
#include <16f877.h>
#device ADC=10

#USE DELAY(CLOCK=4000000) /* Using a 4 Mhz clock */
#FUSES XT,NOWDT,NOPROTECT, NOPUT, NOBROWNOUT,NOLVP

int i,j;
unsigned int8 adcValue;
set_tris_c(0x00);
set_tris_d(0x00);
float voltage;

void main(void)
{
 //adc
   setup_adc_ports( ALL_ANALOG );
   setup_adc(ADC_CLOCK_INTERNAL);      // Use internal ADC clock.
   set_adc_channel(0);
   {
     while(1)
     {
       for (i=0;i<=0;i++)
       {
         output_d(i);
         {
           for (j=2;j<=14;j++)
           {
             output_c(j);
             {
               output_high(PIN_D4);
```

```
output_low(PIN_D5);

delay_ms(1000);

output_high(PIN_D4);
output_low(PIN_D5);

delay_ms(1000);

output_low(PIN_D4);
output_high(PIN_D5);

delay_ms(1000);

output_low(PIN_D4);
output_high(PIN_D5);

delay_us(50);       // Delay for sampling cap to charge
adcValue = read_adc();    // Get ADC reading

while(1)

  {
   printf("\033[2J");           //clear hyperterminal screen

   for(i=0;i<28;i++)
   {


   delay_us(50);       // Delay for sampling cap to charge
   adcValue = read_adc();    // Get ADC reading
   voltage = 1.000 * adcValue / 1023.000;

   //printf("\033[2J");                  //clear hyperterminal screen
```

```
            printf("\n\n");
            printf("Pair Voltage %d : %f V\n",i,voltage);
            delay_ms(500);


            //printf("\033[2J");                //clear hyperterminal screen
            printf("\n\n");

            }
          }

        delay_ms(1000);
      }
    }
  }
}

for (i=1;i<=13;i++)
{
  output_d(i);
  {
    for (j=i+2;j<=15;j++)
    {
      output_c(j);
      {
        output_high(PIN_D4);
        output_low(PIN_D5);

        delay_ms(1000);

        output_high(PIN_D4);
        output_low(PIN_D5);

        delay_ms(1000);
```

```
output_low(PIN_D4);
output_high(PIN_D5);

delay_ms(1000);

output_low(PIN_D4);
output_high(PIN_D5);

delay_us(50);       // Delay for sampling cap to charge
adcValue = read_adc();    // Get ADC reading

while(1)

  {
   printf("\033[2J");              //clear hyperterminal screen

   for(i=0;i<28;i++)
   {


   delay_us(50);       // Delay for sampling cap to charge
   adcValue = read_adc();    // Get ADC reading
   voltage = 1.000 * adcValue / 1023.000;

   //printf("\033[2J");                  //clear hyperterminal screen
   printf("\n\n");
   printf("Pair Voltage %d : %f V\n",i,voltage);
   delay_ms(500);


   //printf("\033[2J");                  //clear hyperterminal screen
   printf("\n\n");
```

```
                }
              }

            delay_ms(1000);
          }
        }
      }
    }
  }
}
}
```