PROCESS TOMOGRAPHY

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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TRONOH, PERAK

June 2007

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.

Faziatul Alhana Ahmad Fuad

ABSTRACT

In order to improve the design and control of Process Tomography, the project is presented in this study. Process tomography is a process of measuring electrical signals by using specific types of sensor. The sensors are arranged around an object, such as vessels or pipelines, to examine the internal characteristics of the subject. The information on the nature of the subject is obtained by reconstructing the measurements from the sensors into a 2-D or 3-D image. There are many methods that can be applied in process tomography. This includes optical tomography, resistive tomography, and acoustic tomography. The method used for this study is Electrical Impedance Tomography (EIT). EIT is a tomographic imaging method which enables the internal impedance of an object to be imaged with the use of a ring of external electrodes. The author had done researches and studies regarding Process Tomography and EIT to obtain information of the process. The hardware part of the system consists of the sensor for the signal and the impedance measurement circuit of the process tomography. Meanwhile, the software part includes the MATLAB program which is used for reconstructs the signals and displays the results. In this project, the author concentrates on the hardware circuit design and data acquisition system for EIT.

ACKNOWLEDGEMENTS

My utmost appreciation to my Final Year Project supervisor, Dr. Taj Muhammad Baloch, who has guided me during the completion of this project and patiently examined my work into details in order to produce an outstanding project and paperwork. Without his relentless effort to guide and supervise me, the project will not have been successful.

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LIST OF ABBREVIATIONS

2-D	Two dimensional
3-D	Three dimensional
EIT	Electrical Impedance Tomography
DAS	Data Acquisition System
VCCS	Voltage Controlled Current Source

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Process tomography is a relatively new imaging technique that has managed to excite interest in broad range of disciplines. The process tomography studies began its applications in medical area, and developed to evolve rapidly in industrial applications. The first systems were built in 1970s, which produced a good standard for process tomography development. Later, research studies focused on process tomography were form such as from the teams of University of Manchester Institute of Science and Technology (UMIST), Rennselaer Polytechnic Institute, Morgantown Energy Technology Center and other researcher groups.

Process tomography is a process of measuring the signals by using specific types of sensors which are arranged around an object in order to examine its internal condition [5]. The information on the nature of the subject is obtained by reconstructing a 2-D or 3-D image from the sensors measurements. The instrument components consist of the hardware and software parts. There are widespread applications of process tomography in oil and gas industry since this process brings a lot of benefits for the engineers in order to observe and examine the internal condition of process line or equipment.

There are many types of sensing methods that can be implemented in the process tomography [5]. The methods are based on measurements of transmission, diffraction or electrical phenomena using radiation, acoustic or electrical sensors. The author will concentrate on the electrical methods which can be used in the project. Compared to other methods, electrical properties measurements are suitable to be applied in the industry since the sensors can acquire fast responses from the sensors.

The technique that the author had chose for this project is Electrical Impedance Tomography (EIT). It is one of the industrial process tomography systems, which measures the electrical properties in a specific object. There are widespread applications of EIT in both medical and industrial fields [2]. Basically, the method will image the conductivity distribution within a test volume by making electrical measurements on the surface of the volume. Usually, this involves injecting current through electrodes attached to the surface and measuring the induced voltage on the electrodes.

An EIT imaging system consists of its data collection measurement system (hardware) and its reconstruction algorithm (software) [5]. The hardware part consists of the sensor for the signal and the data control of the process tomography. Meanwhile, the software part includes the program to reconstructs the signals and displays the results. A few sets of electrodes plates are arranged around the specific object to be used as a sensor for the system. Voltage differences are measured between adjacent pairs of electrodes. These measurements are obtained by the electrodes and sent to the image-reconstruction computer. The computer generates the tomography images of the permittivity distribution from the measurements by the sensors.

There are many applications of EIT method. The medical applications include detecting cancerous tumors in breast tissue and monitoring pulmonary or gastric functions. In industry EIT has applications such as monitoring industrial processes and non-destructive testing and evaluating material [3]. EIT can also be applied to image the distribution of oil and water in a pipeline and imaging the flow of substances in a mixing vessel. In some ways industrial applications are more favorable for EIT because it is usually possible to use a rigid, fixed array of electrodes.

1.2 Problem Statement

There are many methods of measuring industrial parameters such as level, temperature, flow, conductivity, pH and pressure. However, mostly all of the methods developed in the industry do not provide information on the internal characteristics of the components being measured. Usually, the data obtained can only be measured in terms of electrical properties such as voltage and current, and unable to display the internal characteristics of the measurement in terms of images. Below the author listed the advantages of obtaining the internal characteristics of the measurements:

- To improve the design and operation of process and equipment
- To obtain precise and accurate quantitative information from inaccessible locations
- To obtain detailed characteristics of a subject for design, measurement and control of multiphase processes.

The sensors used to operate in an industry must suit its industrial environment. It must be designed to be hostile, fast changing, and chemically aggressive. Responding to this demand requires the development of process tomography. The process involves taking measurements around the periphery of an object such as pipelines or process vessels to determine the internal characteristics of the subject. These measurements will be displayed into an image. The tomography system which applies the electrical impedance principle will be developed as to provide a platform in exploring the potential application of process tomography in oil and gas industry.

1.3 Objective and Scope of Study

1.3.1 Objective

- To study on the data acquisition system of Electrical Impedance Tomography (EIT).
- To design a functional hardware system of EIT including the electrodes construction, measurement circuit, and data acquisition system.

1.3.2 Scope of Study

The study on electrical impedance tomography through process tomography application is to be completed within the time frame given which is approximately 13 weeks. For Final Year Project 1 (FYP1), the author aimed to accomplish the study and researches regarding Process Tomography. All the findings will be used to construct the hardware circuit design of EIT in Final Year Project 2 (FYP 2). In order for successful completion of the project, work planning and laboratory experiments are to be performed throughout the semester. This system is required to be developed by following the criteria of EIT for application in oil and gas industry. Generally, EIT principle covering the scopes as follows:

- The introduction and background studies of Process Tomography
- Methods, techniques and applications of Process Tomography
- Construction of EIT sensors and the circuit measurement of the system
- Electronics theory and circuit design in order to develop the control and data acquisition system.
- Developing C language programs to be used with PIC microcontroller
- Testing and troubleshooting of EIT circuit

CHAPTER 2

LITERATURE REVIEW

Generally, tomography is considered as an imaging tool for medical examination purposes [8]. The applications include imaging of heart and lung function in the thorax, screening for breast cancer and brain function and gastric emptying. There are several other applications as well such as imaging intra-pelvic venous congestion and limb plethysmography, apnoea monitoring and intra-abdominal bleeding or fluid. Medical applications generally do not require high frame rates, and use excitation signals of low magnitude to prevent damage to the individual. However, the concept of tomography and its non-invasive way of imaging is not restricted to the medical field. Tomography has been developed into a reliable tool for imaging numerous industrial applications. This field of application is commonly known as Industrial Process Tomography (IPT) or simply Process Tomography (PT).

Currently, there are many different techniques of sensors that can be used based on measurements of transmission, diffraction or electrical phenomena using radiation, acoustic or electrical sensors. These include infrared, optical, X-ray and Gamma-ray tomographic systems, positron emission tomography (PET), magnetic resonance imaging (MRI), and sonic or ultrasonic tomographic systems [5]. Each of these techniques has its advantages, disadvantages and limitations. The choice of sensing system is determined by many factors. These include the nature of components contained in the subject, the desired resolution of imaging, cost of the equipment, the information sought from the process and its intended purposes, the process environment, the size of the process equipment and the length scale of the phenomena being investigated, human resources needed to operate it, and potential hazards to the personnel involved.

Another method is Electrical Tomography Method which includes Resistance, Capacitance and Impedance Tomography. It provides fast response which up to 200 images per second, simple to operate, has a rugged construction and is sufficiently robust to cope with most industrial environments. The apparent drawback of electrical tomography is its relatively low spatial resolution - typically 3-10% of a pipe diameter. However this is sufficient for many practical industrial applications. Below are the examples of tomographic techniques used in process industries:

Table 1: Examples of process tomography techniques in process industries

Process application	Sensing method
Microstructural characterization of components, particles, pastes, foams, filters (1-10000μm)	Magnetic resonance imaging Neutron tomography X-ray microtomography Optical tomography
Liquid mixing and multiphase flow (0.01-0.5 m)	Optical tomography Resistive tomography Capacitance tomography Acoustic tomography
Powder mixing, transport, and conveying (0.01 – 0.5 m)	Capacitance tomography Electrodynamics tomography
Groundwater monitoring and soil remediation (0.01-0.5m)	Impedance tomography
Atmospheric pollution monitoring (50 m-10 km)	Laser absorption imaging
Oilfield reservoir exploration (50 m -50 km)	Acoustic velocity imaging Acoustic diffraction tomography

Electrical Impedance Tomography (EIT) is a recently developed tomographic imaging technique, which enables the internal impedance of an object to be imaged with the use of a ring of external electrodes. By computing electrical conductivity within the subject, the internal conditions of the subject can be imaged [4]. EIT uses low frequency electrical current to probe the conductivity of the subject. . The electrodes are placed on the surface of the pipe and an alternating current is supplied to the electrodes. By injecting known amount of currents and measuring the resulting electrical potential at points of the boundary of the body, it is possible to invert such data to determine the conductivity or the resistivity of the region of the body probed by the currents. The image reconstruction is computed based on the voltage data. The reconstructed image presents two dimensional slices of the three dimensional conductivity distributions.

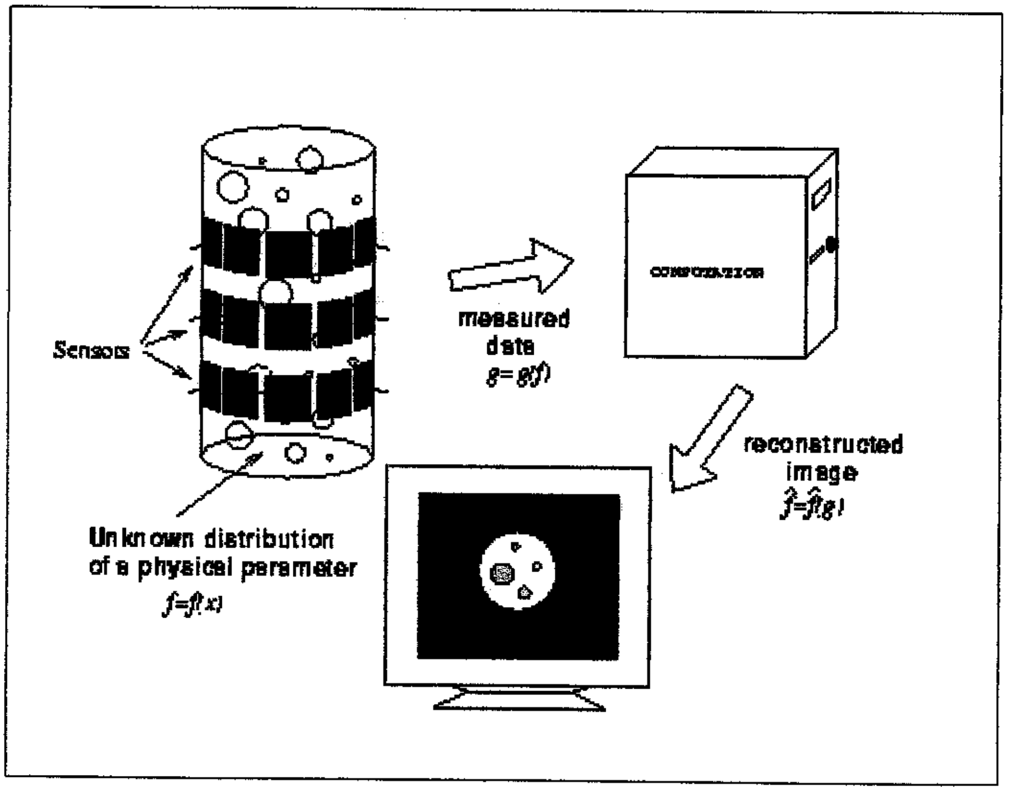

Figure 1: Block Diagram of EIT Method in Process Tomography

EIT applications improve the operation and design of processes handling multi-component mixtures by enabling boundaries between different components in a process to be imaged in real-time using non-intrusive sensors [8]. By using the sensors arranged around the object, the internal conditions can be imaged. This reveals information on the nature and distribution of components within the sensing zone. The sensor output signals depend on the position of the component boundaries within their sensing zones. The tomographic image of the cross-section can be viewed by using software. This will provide identification of the distribution of mixing zones in the subjects correspond to any projects. The image data can be analyzed quantitatively for subsequent use to improve process control or to develop models to describe individual processes.

Compared with techniques like computerized x-ray tomography and positron emission tomography, EIT is cheaper, smaller in size and requires no ionising radiation. Further, EIT can in principle produce thousands of images per second. The major drawbacks of this technique are its low spatial resolution, and large variability of images between subjects.

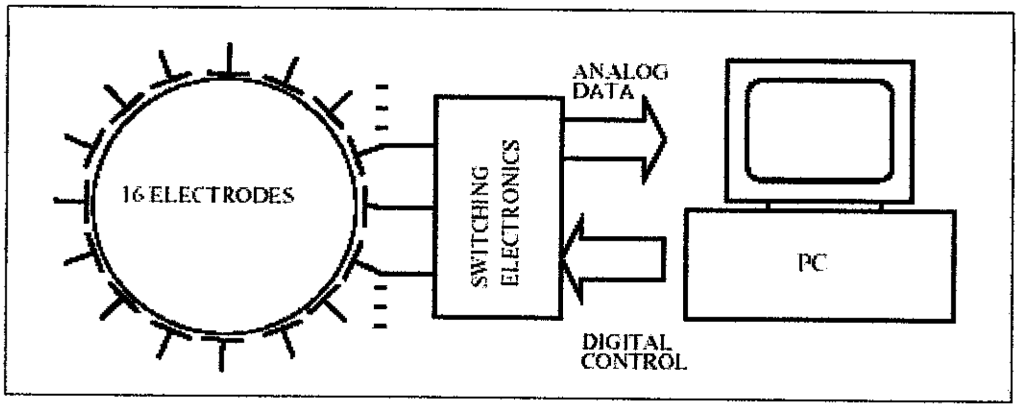

Figure 2: An EIT measurement system

In the industrial field typical applications are imaging the distribution of oil and water in a pipeline and imaging the flow of substances in a mixing vessel. In some ways industrial applications are more favorable for EIT because it is usually possible to use a rigid, fixed array of electrodes. The fixing of electrodes on the human body is one of the residual problems facing medical EIT.

Below are the examples of image reconstructions that have been developed by the earlier researchers in various applications [6]:

i) Flow

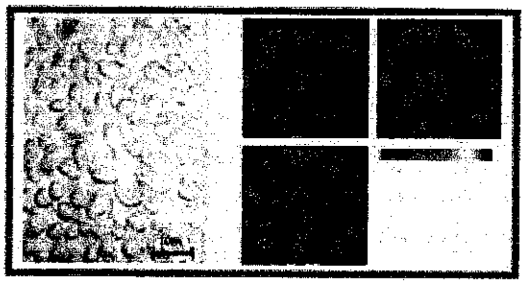

Figure 3: Bubbly flow

Figure 4: Turbulent flow

ii) Mixing

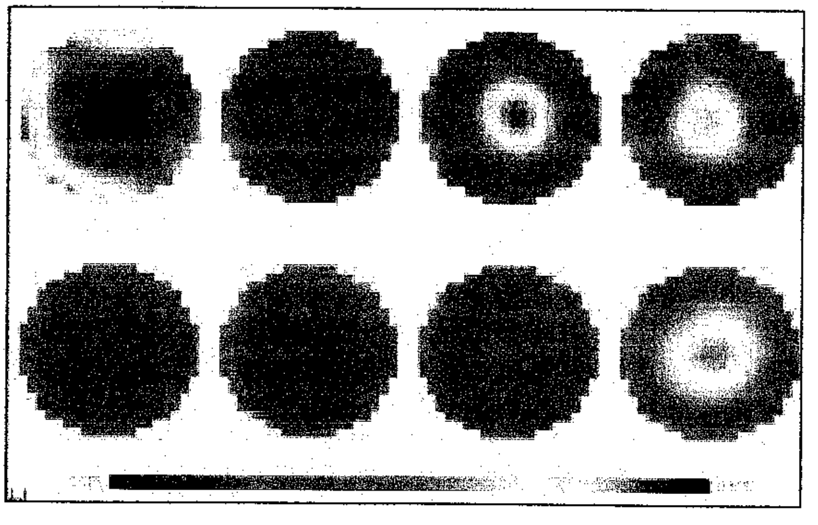

Figure 5: The distribution of gas over 8 measurement planes in a gas/liquid reactor

CHAPTER 3

METHODOLOGY

3.1 Project Planning

There are procedures to be followed in order to carry out this project. This is to ensure that the project flow is smooth and can be accomplished within the given frame time. The first task to be accomplished is to study the literature review and research regarding Process Tomography in general and specifically in Electrical Impedance Tomography (EIT). The example of EIT systems that have been implemented and the most recent applications are taking into account. The systems are compared and the best and the simplest systems are analyzed. The study of each part of the circuit namely the current generation circuit, multiplexing technique, and microcontroller unit needs to be done.

After completing the first part of this project, the second part is designing the circuit to be used as data acquisition system (DAS) in this project. This will include developing the dual current source circuit, multiplexer circuit, and the control unit circuit. Each part of the circuit needs to be simulated and tested before connecting them as a whole system. A program using C programming language needs to be built in order to operate the microcontroller unit.

The next part of this project is to design and fabricate the prototype of the sensors used in the system. Materials to be used for the electrodes are analyzed and the best choice will be implemented. The sensors will be connected to the circuit in order to test and troubleshoot the circuit construction. A series of experiment results on the DAS will be measured and recorded to obtain the image. This project will be carried out in two semesters' duration. The first part will be completed in the first semester and the second part in the second semester. The project flow chart is shown in Figure 6

3.2 Literature Review and Research

In order to obtain fully understanding of this project, the previous research works are studied. The research involves in this study scope are as followed:

- The basic principle of process tomography and its early development in the industry.
- The various sensing methods used in process tomography and its typical applications.
- The basic components of the sensors technique used in this study which is electrical impedance tomography (EIT) and scope of studies for each area.
- The hardware part of this project namely the electrode construction, data acquisition system (DAS), data processing techniques and the image reconstruction.
- Analogue and digital electronics theory for the circuit construction.
- Microcontroller theory and applications, the type of IC used, and the functions of microcontroller unit in this circuit.
- C programming language to be used for microcontroller operation.

Researches and literature reviews of all the scopes listed above need to be completed in order to develop a working data acquisition system. Reference books and journals from early researches are studied and the systems are compared to obtain the best solutions. The latest technology, techniques and applications can be gained from reading the technical papers and can be applied in this project. These stages provide important and useful knowledge in order to design the best and the simplest hardware implementation. Due to that, more time needs to be consumed in this stage to provide the best solution.

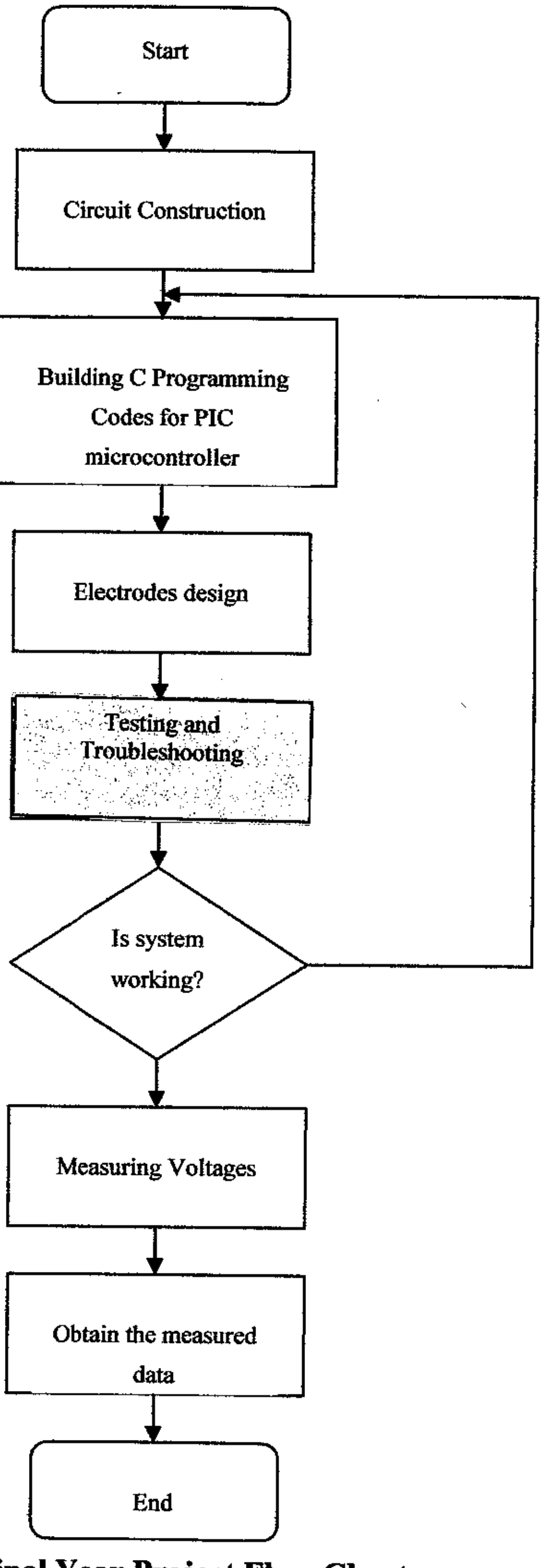

Figure 6: Final Year Project Flow Chart

3.3 Electrode Construction

Impedance sensors consist of a several sets of electrodes that are positioned at equal intervals at fixed locations around an object. They are designed in such a way that they make electrical contact with the fluid inside the object but do not affect the normal mass transfer within the process. These electrodes will be connected to the data acquisition system by a set of simple wires to provide the electrical conduction. Aluminium plate will be used as the electrodes in this project. It is selected because of its ability as a good thermal and electrical conductor. In industrial applications, the material used for the electrodes depends largely on the process operation environment. The electrodes must be possible to abstract maximum amount of information from the inside of the object and hence acquire the possible images.

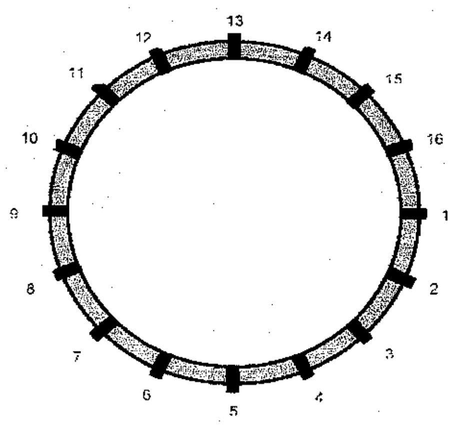

Figure 7: Electrodes arranged at equal interval around an object

In this project, adjacent method is used as an EIT sensing system. As shown in the Figure 8, current is applied to a pair of adjacent electrodes. The voltage differences between all the other adjacent pairs of electrodes are measured, excluding the pair for which the electrode is an electrode carrying current. Current is then applied through the next pair of electrodes and the voltage measurements are repeated. This procedure is repeated for all pairs of electrodes until a full rotation of electrical field around the object cross-section is obtained.

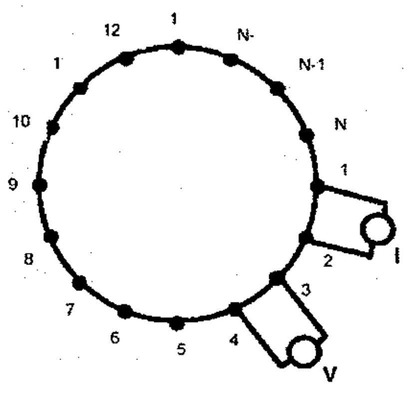

Figure 8: Adjacent Method

In total, the adjacent measurement method will produce N^2 measurements, where N is the number of electrodes. Out of the total number of measurements, only N(N-1)/2 are independent. In this method, the voltage will not be measured at a current-injecting electrode. This is due to the presence of electrical resistance between the electrode and the measurement object, making the measurements slightly inaccurate. Therefore, the total number of independent measurements is now reduced to N(N-3)/2.

In this project, the author uses eight electrodes. From the formula, the total measurements obtained are 20 measurements. These measurements will be displayed at Hyper Terminal program in the personal computer. PIC microcontroller is used to receive and transmit the data from the whole circuit to computer. Theoretically, the image resolution developed by using eight electrodes is relatively poor compared to higher number of electrodes in use. Increasing the number of electrodes will definitely increase the total measurements taken, hence increasing the image resolution of the object. However, the image reconstruction part is beyond the scopes of the project, hence the total number of measurements does not take into account.

3.4 Data Acquisition System Design (DAS)

In order to construct a tomographic image in an object, a functional data acquisition system needs to be developed. The scopes of this objective include the design and construction of the current generation, multiplexer, voltage measurement and central control unit design. These circuits will be connected together to obtain the voltage measurements at the output of the microcontroller and will be displayed Hyper Terminal program. The specifications of each part of the circuit construction are outlined as below:

3.4.1 Current Generation

Most of the current sources used in EIT systems are more appropriately called voltage to current converters, since they produce an output current that is proportional to an input voltage . The current source in an EIT system must be able to deliver current with desired precision over a specified frequency range to load impedances within an expected range of values. In this project, the voltage controlled current source (VCCS) is used to produce the constant current as a supply to the system. Figure 9 shows a possible implementation of a VCCS:

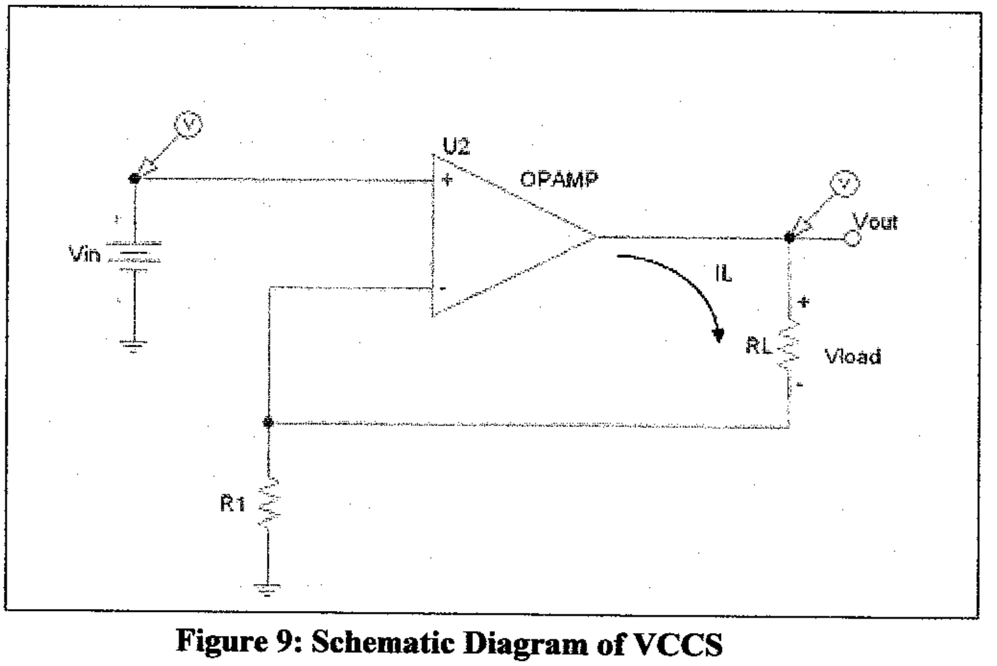

Figure 9: Schematic Diagram of VCCS

The node equation at the inverting input is as follows:

$$\frac{V_{in}}{R} + \frac{V_{in} - V_{out}}{R_L} = 0$$

From the circuit above we can see that $V_{out} - V_{in} = V_L$. To get the equation describing the operation of the current-source, we equate $I_L = V_L/R_L = V_{in}/R$ (load current is independent of the load resistance). Hence, the equations relating V_{out} and V_{in} are as follows:

$$V_{out} = (R + R_L)\frac{V_{in}}{R}$$

$$I_L = \frac{V_{in}}{R}$$

The current generation circuit above is simulated in PSPICE and different values of R load will be used to observe the change in voltage output, load voltage and load current. The calculated values of load current will be compared to the measured values and will be discussed in Chapter 4.

In previous traditional EIT systems, high frequency sinusoidal waveform is used as the excitation source, which in turns introducing signal demodulation circuits such as filters. These extra circuits decrease the speed performance of the whole system. Due to that, bi-directional current pulse is used to excite the electrodes in order to improve the measurement speed. In this project, analog CMOS switch HCF4066BE is used in the circuit to generate the bi-directional current. The IC consists of 4 bi-polar switches which let the current flows through when the switch (control pin) is held at a high voltage level. Otherwise the switch will open and no current will flow.

In the positive half cycle, switches S1 and S3 are closed, while switches S2 and S4 are open. The current flows from electrode A to electrode B. In the negative half cycle, S1 and S3 are open while S2 and S4 are closed. As a result, the current is reversed, flowing from electrode B to electrode A. The sequence of the switches is summarized in Table 3 below. Figure 10 shows the schematic diagram of bi-directional current source:

Table 2: Bi- directional current pulse sequence

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

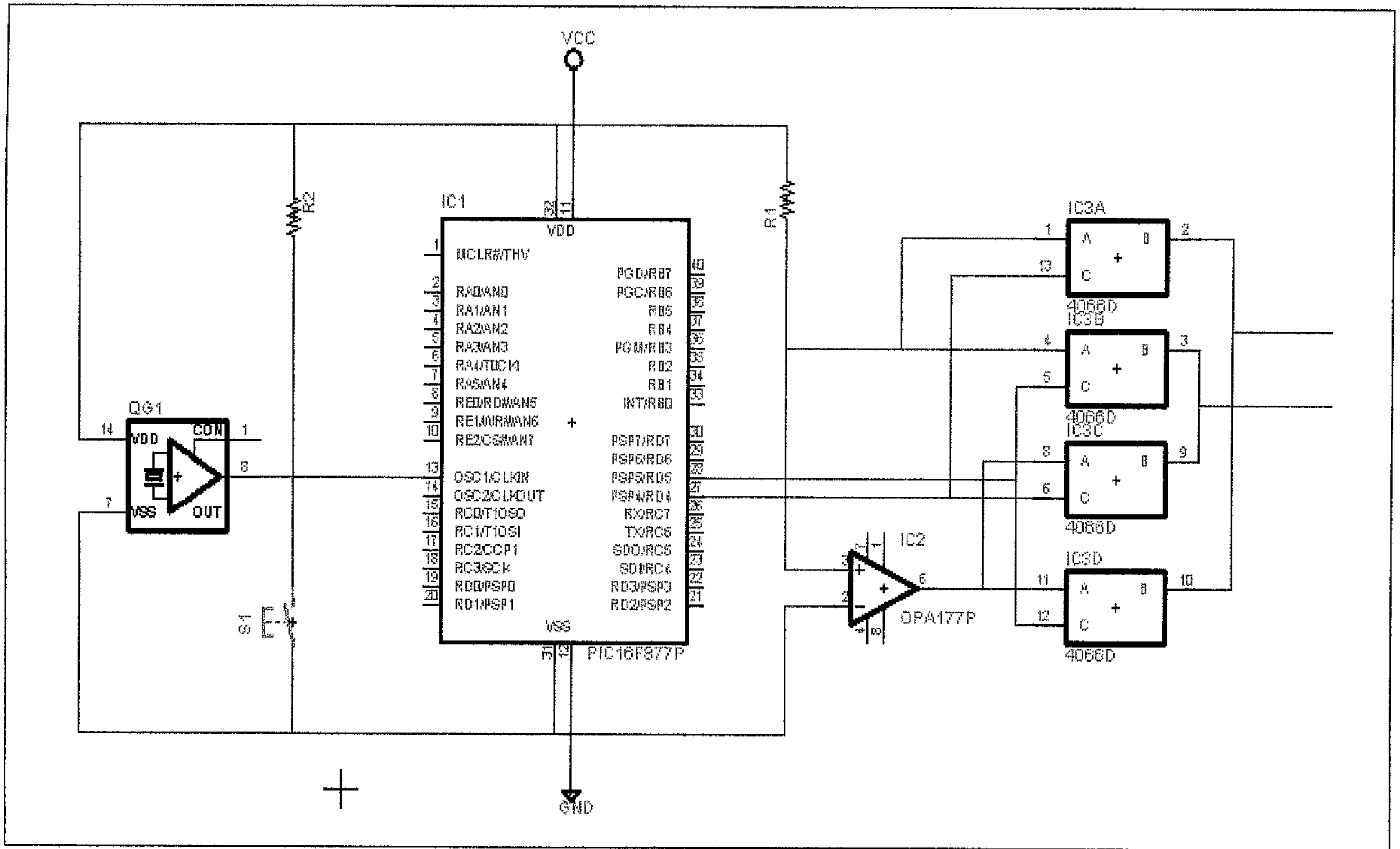

Figure 10: Schematic Diagram of Bi-Directional Current Source

3.4.2 Multiplexer

In order to perform data acquisition in 8-electrodes mode, a multiplexer circuit is necessary for switching the current source and voltage measurement components between different electrodes. In this project, the multiplexer circuit consists of four 8 × 1 MC14051B analogue multiplexers. Two multiplexers are used for current injection channel while the other two multiplexers are used for voltage measurement channel. The multiplexers will select which pair of electrodes will be used and measured in one particular time. In adjacent method, two electrodes will be used for current injection. The voltage difference between all other adjacent pairs will then be measured excluding the electrodes used for the current injection. Current then applied to another pair of adjacent electrodes and the voltage measurements are repeated until the full rotation of electric field of the object is obtained. The multiplexers' outputs will be fed into PIC microcontroller and will be processed. The schematic diagram of multiplexer circuit is shown as in Figure 11.

3.4.2.1 Multiplexer Sequence

As the author has discussed before, the multiplexers will be used for current injection and voltage measurement. The number of multiplexer sequence will depend on the number of electrodes used. Since the author is using 8 electrodes in this project, the total voltage measurements will be 20. This can be obtained from the standard formula:

$$\begin{aligned}\text{Total number of measurements} &= N(N-3)/2 \\ &= 8(8-3)/2 \\ &= 20\end{aligned}$$

In order to obtain the 20 measurements, the multiplexers are designed to be as in the Table 2 (Note that MUX1 and MUX2 are multiplexers used for current injection, while MUX3 and MUX4 are multiplexers used for voltage measurement. Numbers indicates the electrodes)

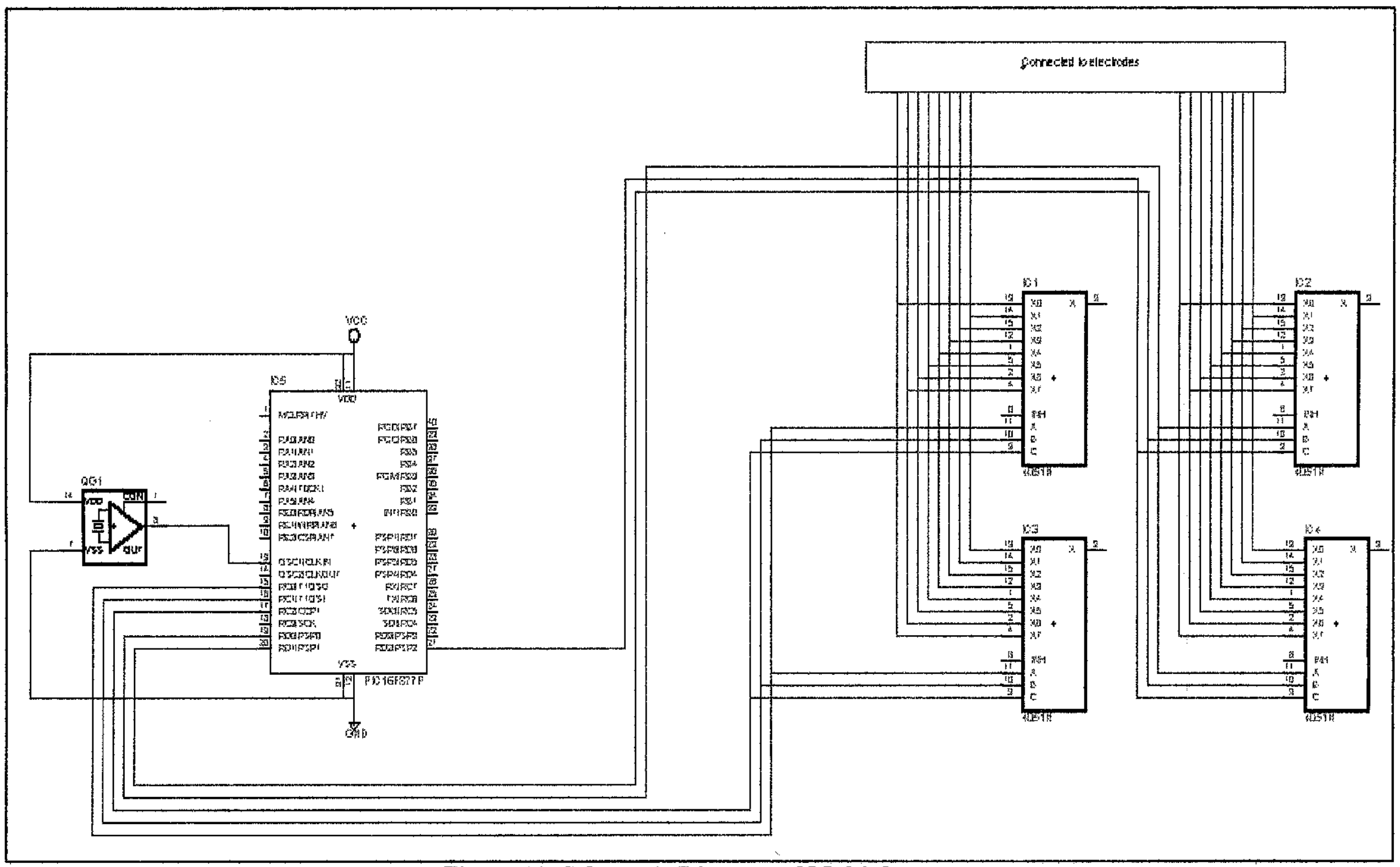

Figure 11: Schematic Diagram of Multiplexer

Table 3: The sequence of multiplexers

Sequence	Current Injection		Voltage Measurement	
	MUX1	MUX2	MUX3	MUX4
1	1	2	3	4
2			4	5
3			5	6
4			6	7
5			7	8
6	2	3	4	5
7			5	6
8			6	7
9			7	8
10			8	1
11	3	4	5	6
12			6	7
13			7	8
14			8	1
15	4	5	6	7
16			7	8
17			8	1
18	5	6	7	8
19			8	1
20	6	7	8	1

3.4.2.2 Truth Table for Multiplexer

The multiplexers switching for current injection and voltage measurement are controlled via control logic by using microcontroller PIC16F877. The truth table shown in Table 3 indicates the sequence of every multiplexer during certain time duration.

Table 4: Truth Table of Multiplexers

<table>
<tr><th rowspan="2">Sequence</th><th colspan="3">Current Injection</th><th colspan="3">Voltage Measurement</th></tr>
<tr><th colspan="3">MUX1 & MUX2</th><th colspan="3">MUX3 & MUX4</th></tr>
<tr><td>1</td><td rowspan="5">0</td><td rowspan="5">0</td><td rowspan="5">0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>2</td><td>0</td><td>1</td><td>1</td></tr>
<tr><td>3</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>4</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td>5</td><td>1</td><td>1</td><td>0</td></tr>
<tr><td>6</td><td rowspan="5">0</td><td rowspan="5">0</td><td rowspan="5">1</td><td>0</td><td>1</td><td>1</td></tr>
<tr><td>7</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>8</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td>9</td><td>1</td><td>1</td><td>0</td></tr>
<tr><td>10</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>11</td><td rowspan="4">0</td><td rowspan="4">1</td><td rowspan="4">0</td><td>1</td><td>0</td><td>0</td></tr>
<tr><td>12</td><td>1</td><td>0</td><td>1</td></tr>
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<tr><td>14</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>15</td><td rowspan="2">0</td><td rowspan="2">1</td><td rowspan="2">1</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td>16</td><td>1</td><td>1</td><td>0</td></tr>
</table>

17				1	1	1
18	1	0	0	1	1	0
19				1	1	1
20	1	0	1	1	1	1

3.4.3 Signal Conditioning Circuit

Before the measured analogue voltages obtained from the multiplexer circuit is being converted to digital values, signal conditioning circuit needs to be developed in order to obtain only one input as an analogue values. The analogue values will then be converted to digital values by connecting the output of signal conditioning circuit to pin A0 of PIC16F877. Hence, only one pin of the PIC16F877 is required in the circuit to convert analogue to digital value. Furthermore, the signal conditioning circuit is constructed by means of reducing the signal error from the analogue values.

The signal conditioning circuit that the author has developed in this project consists of differential amplifier and instrument amplifier. It is unnecessary for the author to develop filtering circuit since this project uses bi-directional current pulse to excite the electrodes. During each half cycle, the current is kept constant, and similar to a square wave. It was proved that the difference of voltage measured between the sense electrode pair is nearly a perfect square wave proportional to the drive current and the conductivity distribution in the medium. Therefore, signal demodulation is not needed and high measurement speed can be obtained. Figure 13 shows the connection of signal connection circuit with multiplexers and PIC16F877.

Instrumentation amplifier is a type of op-amp that has been specifically designed to have characteristics suitable for use in measurement and test equipment. This op-amp is applied when accuracy and stability of a circuit is required. Along in the instrument amplifier is differential amplifier. The differential amplifier amplifies the difference between two input signals (-) and (+). This amplifier is also referred to as a differential-input single-ended output amplifier. It is a precision voltage difference amplifier, and forms the central basis of instrumentation amplifier circuits. The output equation of differential amplifier circuit is given as:

$$V_{out} = (V_2 - V_1)\,\frac{R_2}{R_1}$$

The differential amplifier is usually limited in its performance by the low input impedance of 2R1. Two buffer amplifiers are commonly added to remove this limitation and form the simple instrumentation amplifier. Figure 12 shows the schematic circuit of a simple instrumentation amplifier.

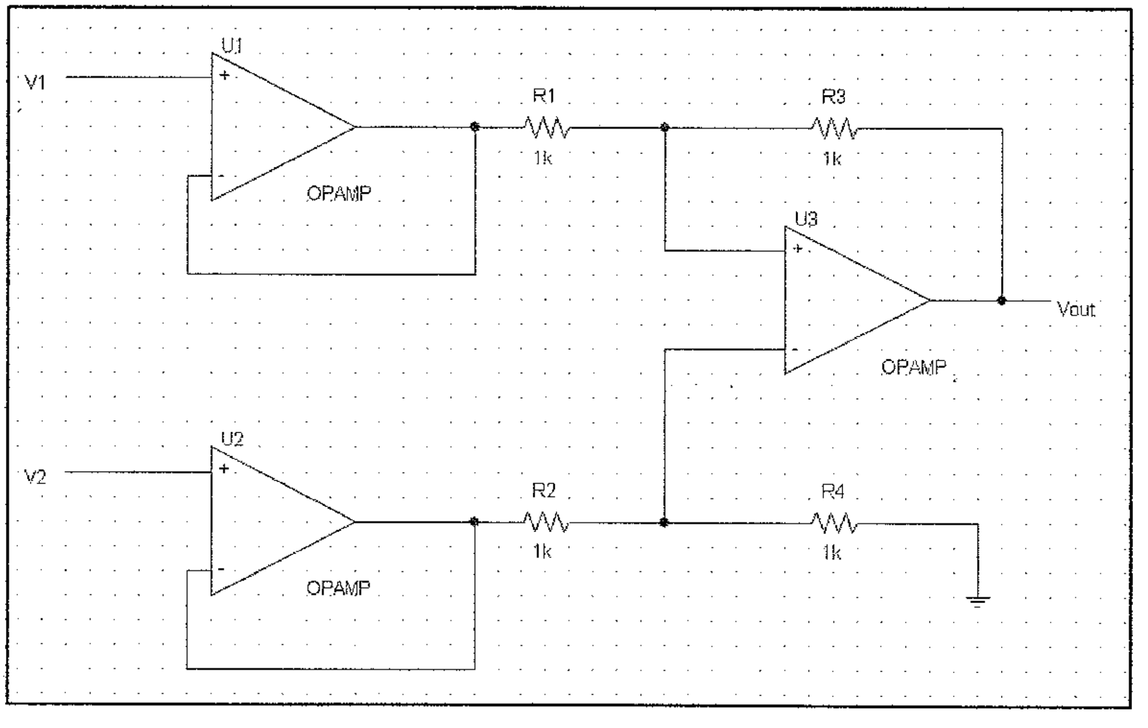

Figure 12: Schematic circuit of a simple instrumentation amplifier

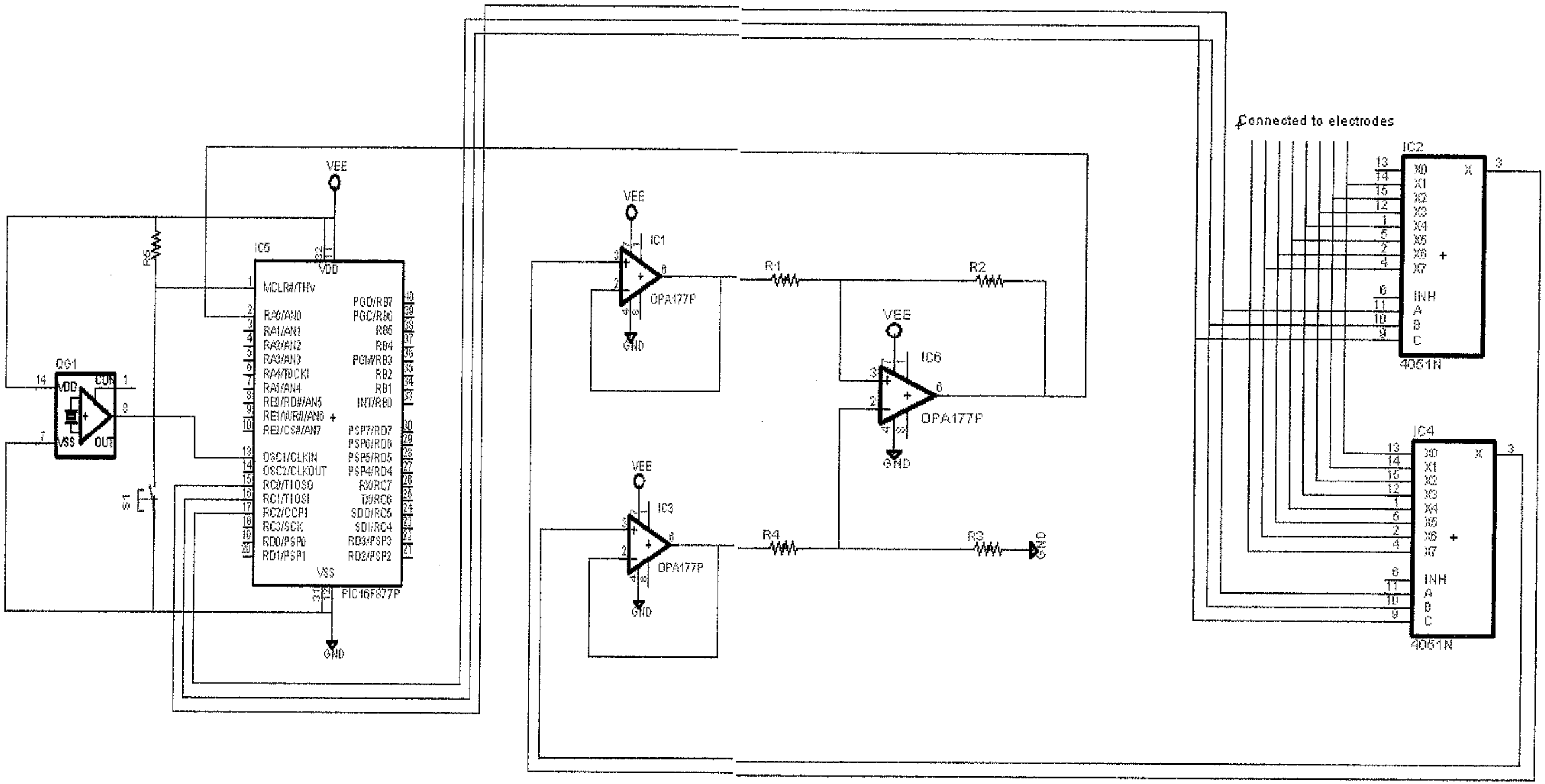

Figure 13: Signal Conditioning Circuit

3.4.4 Central Control Unit

PIC microcontroller is used to synchronize all the measurement circuit and controls the whole process. Due to that, it is always refer as the central control unit of the process. Basically, the major functions of microcontroller are to generate and inject the current signal into the circuit, multiplexer switching for both current injection and voltage measurement and analog to digital conversion. The microcontroller will also be connected to a PC interface circuit to view the voltage measurement in terms of digital values.

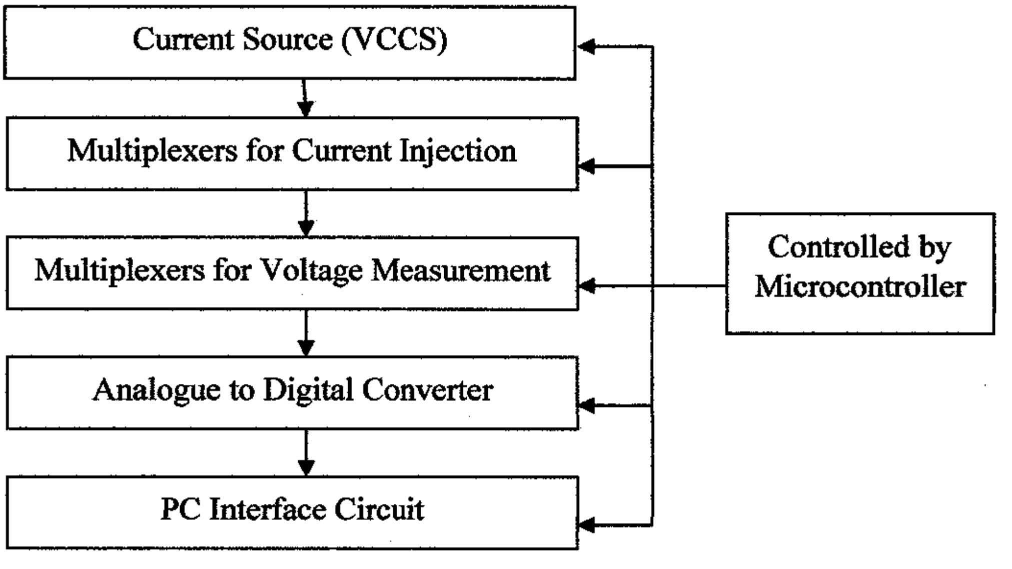

Figure 14: Tomography System controlled by microcontroller

In this project, PIC 16F877 is used as the central control unit. This type of microcontroller is used because it has big capacity of memory, and hence provides available output and input pins for the project. Furthermore, Figure 15 shows the physical pinout of PIC16F877:

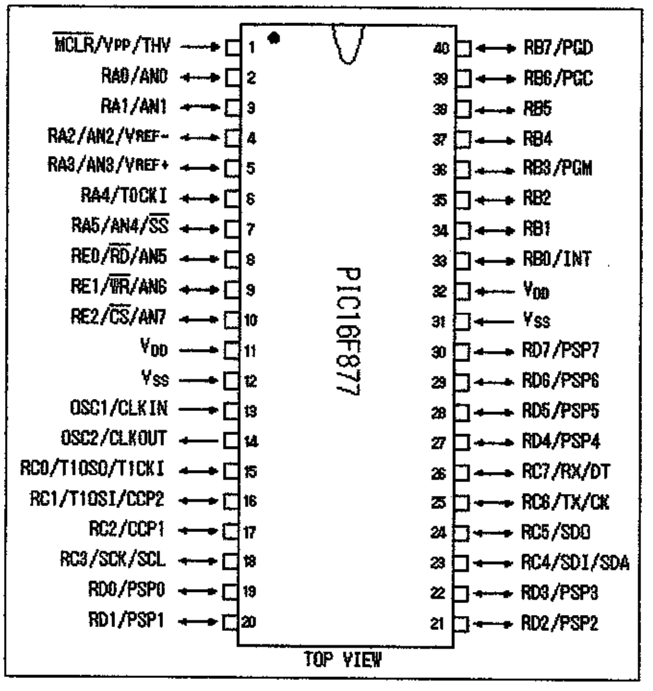

Figure 15: Physical Pinout of PIC16F877

For this project, the output and input pins are as specified as follows:

- **Power Supply and Grounding**

  Power (+5V) and ground (GND) are connected to the PIC through pins Vdd and Vss. The ***dd*** and ***ss*** refer to the **drain** and **source** notation used in the PIC.

  Vdd = 5V and Vss = 0

- **The master clear pin MCLR**

  This is an active low pin that provides a reset feature. Grounding this pin causes the PIC to reset and restart the program stored in the FLASH ROM. At any other time (for running the microcontroller), the MCLR pin should be made logic 1 by connecting it to a +5V supply through a pull-up resistor

- **Oscillator/ External Clock Source Input**

  Pin OSC1/CLKIN will be used to connect with external clock input to generate frequency used for this project.

- **Signal Generation**

  The analogue CMOS switch HCF4066BE is connected to pins RD3 and RD4 to synchronize all the measurement circuits. Port D is bi-directional I/O port, which means it can be configured as an input or an output.

- **Multiplexer switching**

  Port C and Port D are used for multiplexing addressing for current injection and voltage measurement respectively. Both Port C and Port D are bi-directional I/O port. RC0, RC1 and RC2 are connected to the control pins A,B and C of multiplexers 4051 which used for current injection. Meanwhile RD0,RD1 and RD2 are also connected to the control pins A,B and C of multiplexers 4051 for voltage measurement. The output of each port is a 3 bit address from 000 to 111 to control the multipexers.

- **Analog to Digital Conversion**

  The pins in Port A can be used as analog inputs. These analog inputs can be converted to digital output with the build-in analog to digital converter in PIC16F877. Pin RA0 to RA7 can be used for multiple analog input or single analog output. The ADC used in this project is 10 bits ADC.

- **USART asynchronous receiver and transmitter**

  Pins RC6 and RC7 can be used as USART asynchronous transmitter and receiver respectively.

3.4.5 Serial data communication between hardware and 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 which is MAX232. MAX232 helps protecting the processor from possible damage by static that may come from people handling the serial port connectors. Pins RC6 and RC7 can be used as USART asynchronous transmitter and

USART asynchronous receiver respectively. For this project, the author uses the RS232 communication circuit to read the voltage data measured at the electrodes. Pins T1OUT and R1in of MAX232 will be connected to 9 pin connector of RS232 in order to be connected to PC to display the measured voltage. The data will be displayed at HyperTerminal. The configuration at HyperTerminal must set to the same configuration a microcontroller. Figure 16 below shows the connection of PIC16F877, MAX232 and the interface cable of RS232 to the computer.

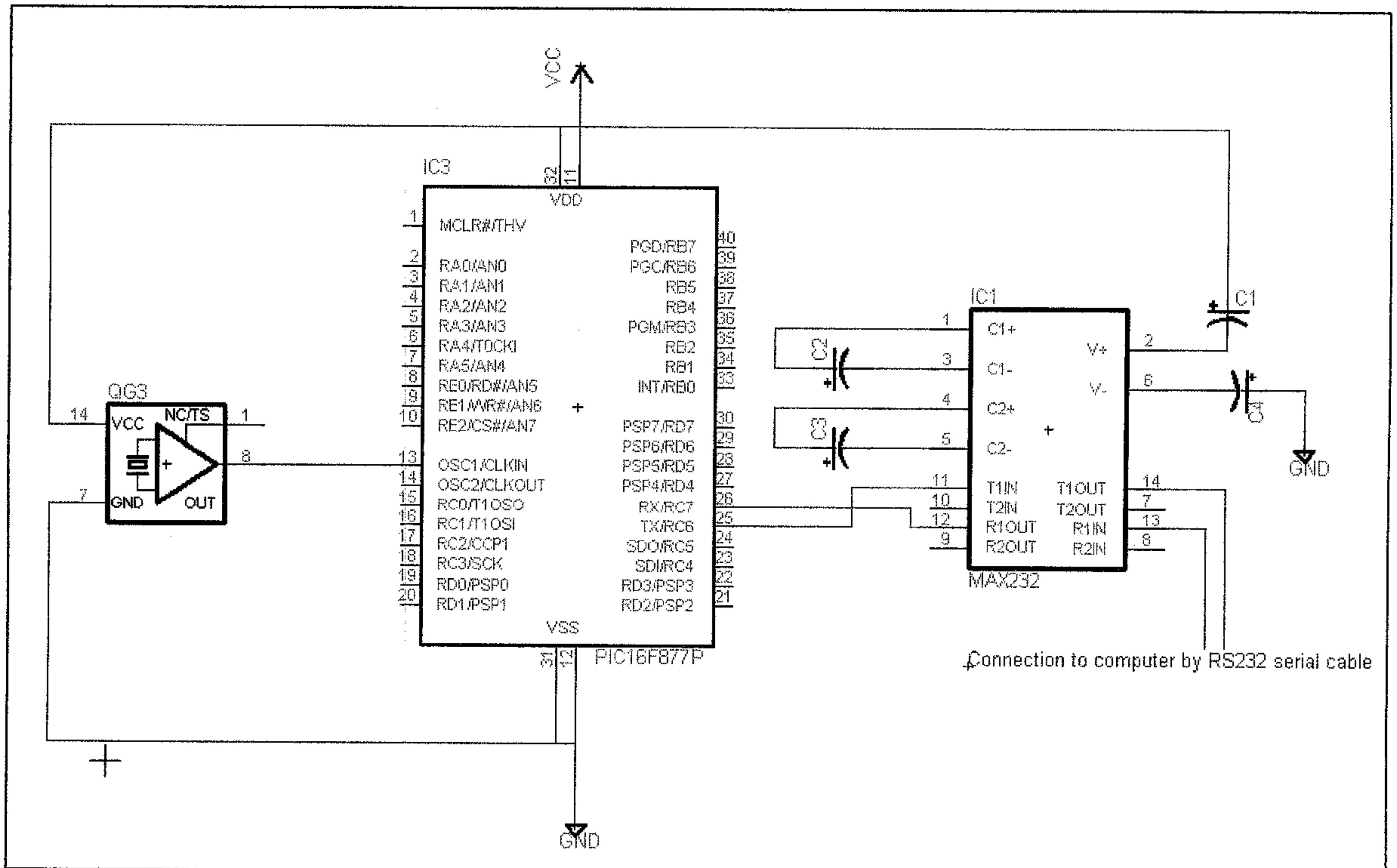

Figure 16: Circuit connection of PIC16F877 and MAX232

CHAPTER 4

RESULTS AND DISCUSSION

Towards completing this project, some experiments are carried out to obtain reliable and accurate measurements. Below are the results obtained during simulation of voltage controlled current source (VCCS):

4.1 Simulation on VCCS

In this project, a current amplitude of 10 mA peak-to-peak needs to be used to supply the system. This value can be obtained with the circuit configuration as in Figure 17. As simulated in the Figure 13, R1 used is equal to 500 ohm and RL used is 100 ohm. The voltage obtained at the output is 6V.

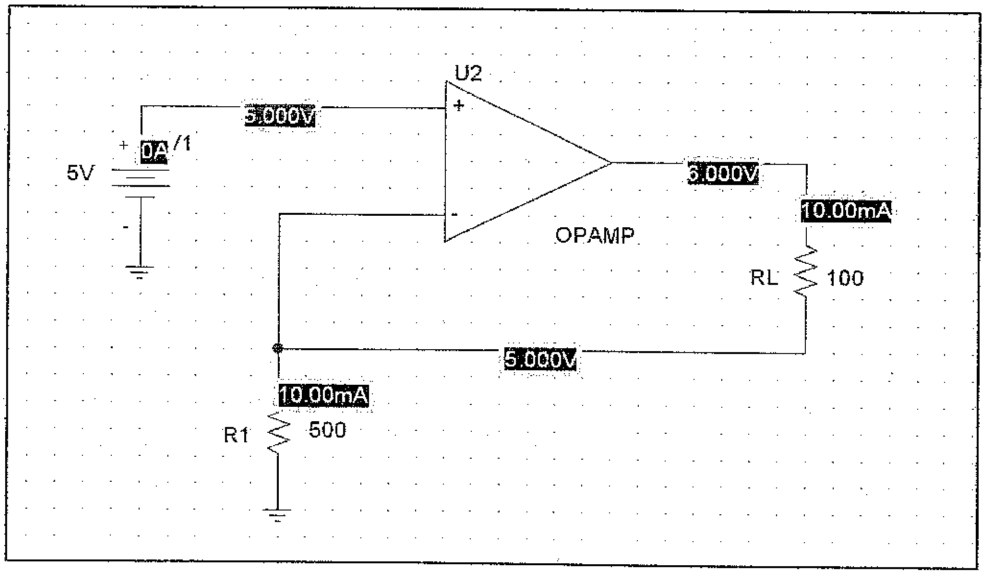

Figure 17: VCCS circuit simulation

From the formula discussed in Chapter 3, the calculated values are as follows:

$$\boxed{V_{out} = \frac{(R_1 + R_L)\,V_{in}}{R_1}}$$

$$V_{out} = (500 + 100)\ 5/500$$

$$= \mathbf{6\ V}$$

$$\boxed{I_L = \frac{V_{in}}{R1}}$$

$$IL = 5V / 500\ ohm$$

$$= \mathbf{10\ mA}$$

From the calculation above, the calculated values of Vout and IL complied with the simulation done on PSPICE. In order to observe the change of IL and Vout with respect to Vin, the values of RL are varied. The values of Vin must be fixed at 5V and R1 at 500 ohm. The objective of this simulation is to obtain 10 mA current. The result of the experiment is shown in Table 4 below:

Table 5: Results of I_L and V_{out} when R_L are varied

RL (ohm)	IL (mA)	Vout (V)
100	10	6
500	10	10
1000	10	15
1500	7.5	15
2000	6	15
2500	5	15

From the results obtained in table above, the maximum allowable value of RL to obtain 10 mA current is 1000 ohm. If RL exceeds 1000 ohm, the load current will decrease and does not compliance with the specification of the project. In conclusion, the maximum value that can be used in the VCCS circuit is 1000 ohm.

4.2 Circuit Construction

The author has developed the VCCS, multiplexer and communication circuits. Figure 18 below shows the connection of the circuit on the breadboard while Figure 19 shows the connection on the Veraboard.

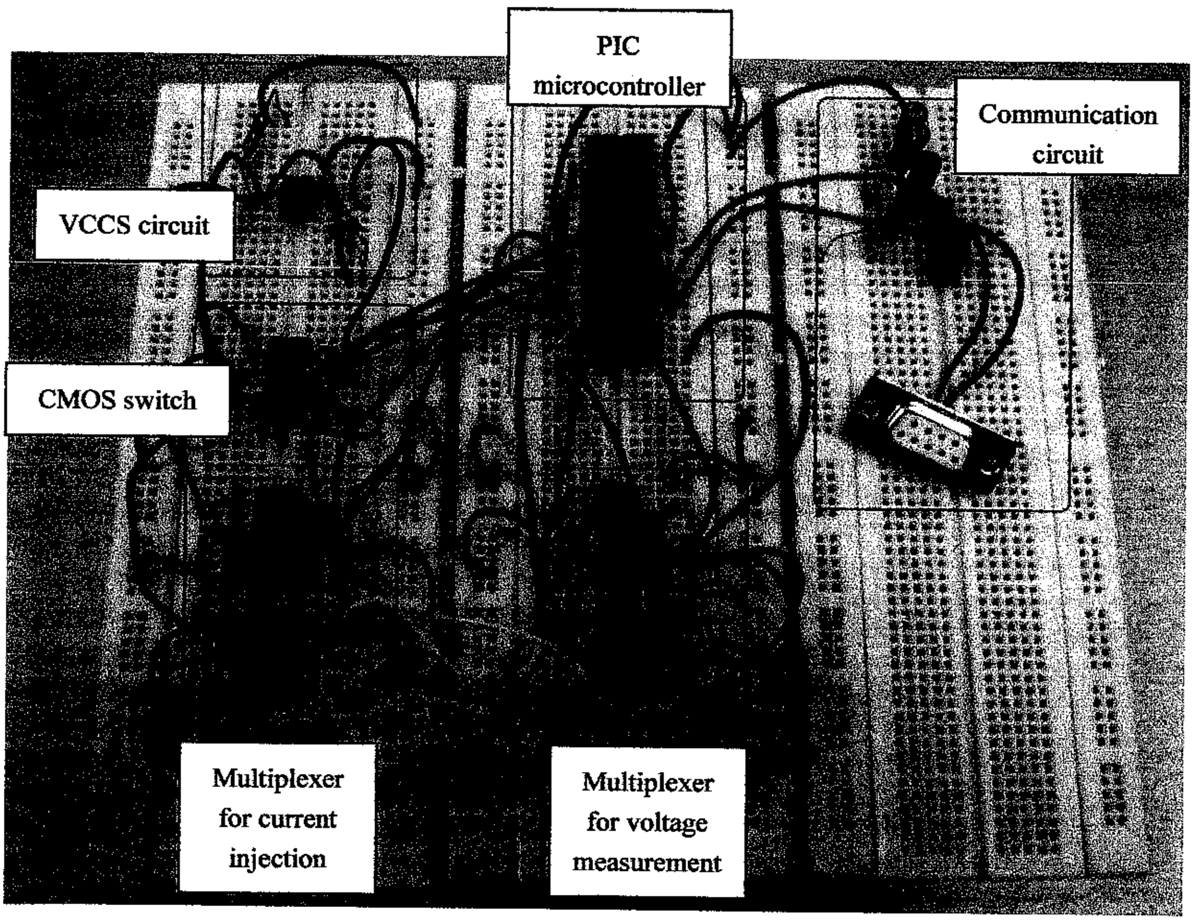

Figure 18: Data Acquisition System Circuit connected on Breadboard

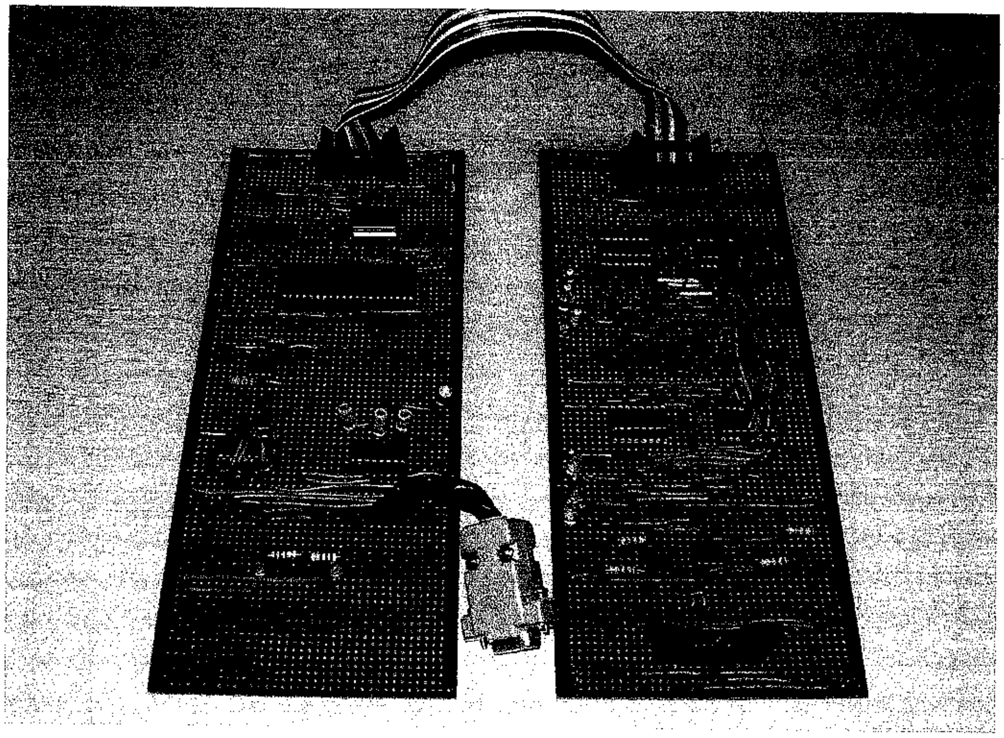

Figure 19: Data Acquisition System Circuit connected on Veraboard

4.2 Electrode construction

For this project, a prototype of a vessel attached with electrodes was designed and implemented. A container with diameter 17 cm and 19 cm in height is used as the vessel. Eight aluminium plates are attached to the container wall using 0.5 cm screw. Below are the figures of the prototype looking from side and top views:

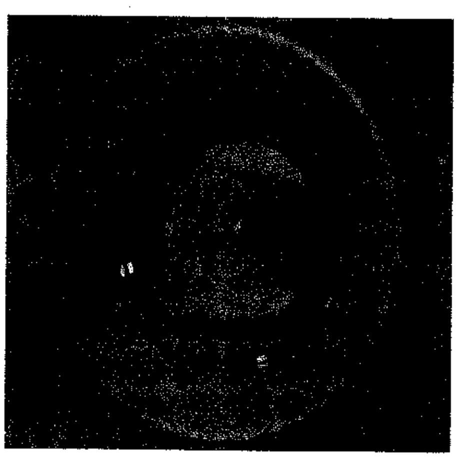

Figure 20: Top View

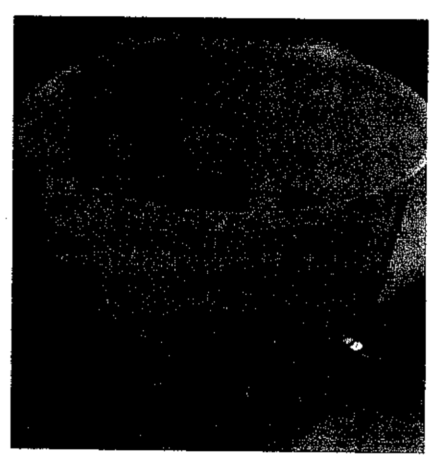

Figure 21: Side View

4.3 Hardware system of EIT

The data acquisition circuit will be connected to the electrodes and to the computer. Figure 20 shows the hardware connection of EIT system.

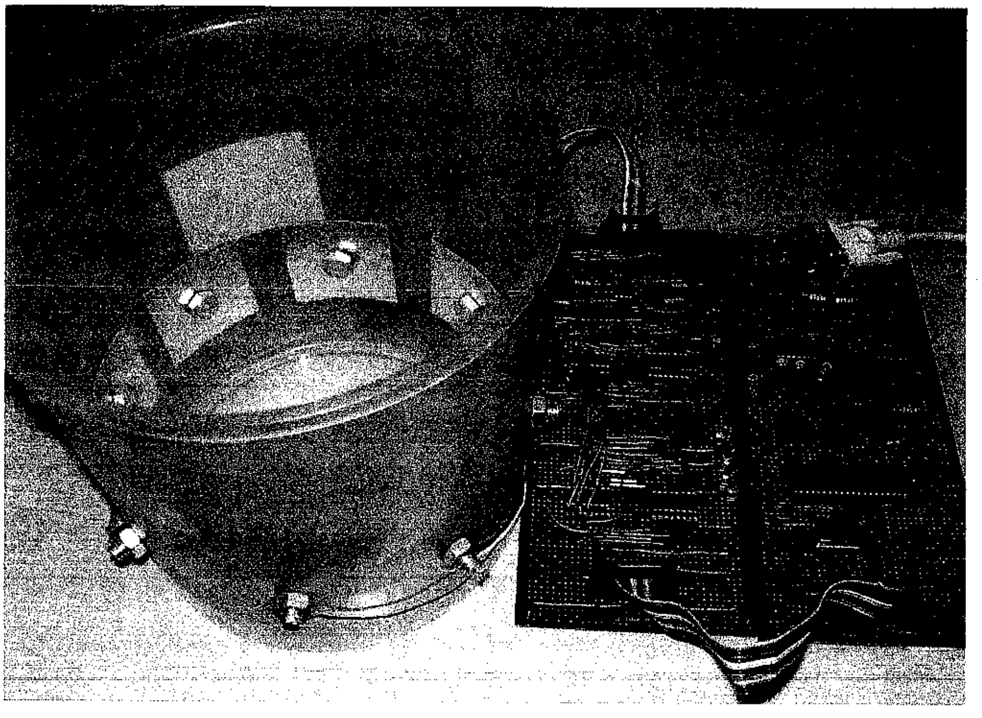

Figure 22: The Hardware System of EIT

4.4 Voltage Measurement

The voltages between electrodes are measured by using the data acquisition system that had been developed. The voltages are measured when there is a bottle in the tank and when there is no bottle in the tank. The difference of the voltages value for both measurements is shown in Figure 22. The values for both measurements are tabulated in Table 6 below:

Table 6: Voltage Measurements With and Without Object

Sequence	Current Injection		Voltage Measurement		Voltage Value (mV) (Without object)	Voltage Value (mV) (With object)
	Electrode Number		Electrode Number			
1	1	2	3	4	33	32
2			4	5	23	24
3			5	6	11	14
4			6	7	25	25
5			7	8	36	36
6	2	3	4	5	32	32
7			5	6	23	24
8			6	7	15	17
9			7	8	26	27
10			8	1	33	33
11	3	4	5	6	33	34
12			6	7	25	26
13			7	8	17	19
14			8	1	25	28
15	4	5	6	7	34	38
16			7	8	25	26
17			8	1	12	16
18	5	6	7	8	37	42
19			8	1	20	24
20	6	7	8	1	35	38

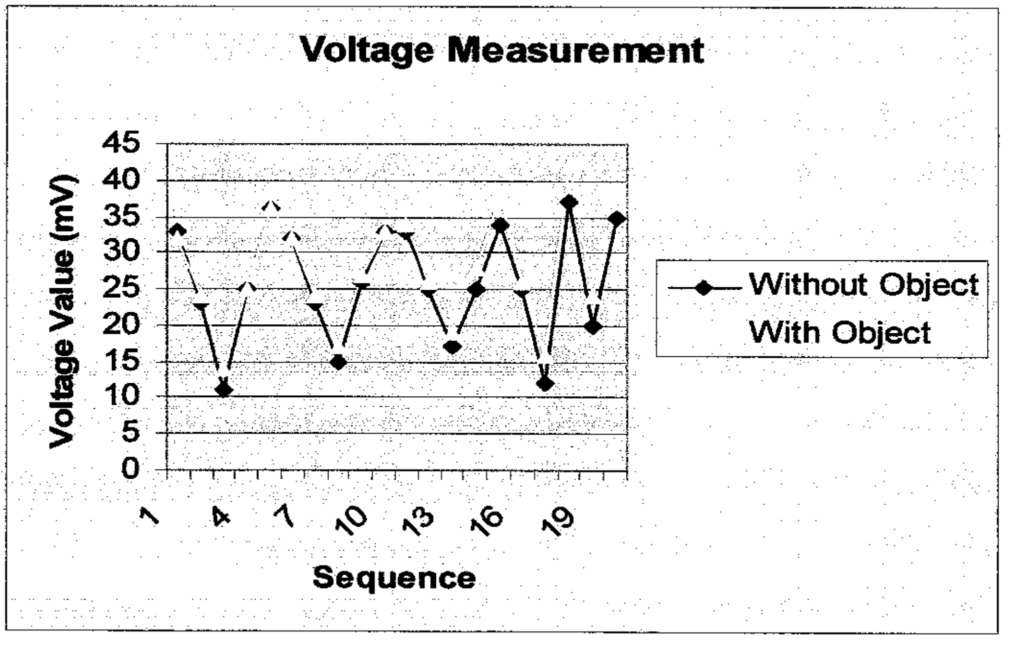

Figure 23: Difference of voltage measurements with and without object.

As we can see from the Table and Figure, there is slightly difference value of voltages between the tank with and without object. This indicates the effect of object within the tank. From the measurement, it can be concluded that the voltage is highest at electrode pair closest to current carrying pair. The voltage decreased when electrode pair away from current injection electrode pair. Voltage is lowest at electrode pair which has longest distance from current injection pair.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Throughout the project implementation, the author has been able to construct the prototype of vessel with the electrodes and the data acquisition system. A series of experiments to verify the connection and feasibility and accuracy of the circuits have been done. This project brings the opportunity for the author to sharpen her skills in designing circuits and developing high level programming language.

While producing the voltage measurement from the data acquisition system, the author noticed that the current injected into the circuit is too small, hence generating small values of voltage difference between the electrodes. The author had difficulties in obtaining the voltage difference due to this reason. The excitation current from the current source needs to be increased to obtain higher value of voltages.

In order to obtain accurate results from this project, the circuit boards as well as the components used need to be examined first before the start of the project. In this project, the author used 8 electrodes. The number of electrodes can be increased to obtain more accurate results. The higher the number of electrodes, the more voltage measurements can be obtained. These voltage measurements are used to reconstruct the image that has been captured. In order to obtain a precise and accurate image, higher number of measurements needed to be used. The maximum number of electrodes that can be used in process tomography as per described by earlier researchers are 32 electrodes.

Furthermore, the whole circuit needs to be designed on the PCB in order to reduce the resistance from the wiring. This will improve the sensitivity of the circuit, producing more accurate voltage measurements. However, due to limited duration of time, the author only managed to design the circuit on the veraboard.

In conclusion, a simple data acquisition has been successfully developed. However, the system can be enhanced and upgraded to a more sophisticated design in the future.

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3. Guizhi Zu, Shuai Zang, Huanli Wu, Shuo Yang, Duyan Geng, Weili Yan, Mingshi Wang, 2005, *The Acquisition Hardware System with Direct Digital Synthesis and Filtered Back-Projection Imaging in Electrical Impedance Tomography.*
4. P.J.Vauhkonen, M. Vauhkonen, T.Salovainen, J.P.Kaipio, 1998, *Three Dimensional Electrical Impedance Tomography Based On The Complete Electrode Model.*
5. R.A William and M.S Back, 1995, *Process Tomography Principles, Techniques, and Applications*, Oxford, Butterworth-Heinemann.
6. Industrial Tomography System http://www.itoms.com/index.htm
7. Electrical Impedance Tomography <http://www.eit.org.uk>
8. Industrial Process Tomography at Manchester University <http://www.tomography.manchester.ac.uk/basic.shtml>

APPENDICES

APPENDIX A

GANTT CHART FOR FINAL YEAR PROJECT

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Project Topic	■													
2	Preliminary Research Work		■	■											
3	Submission of Preliminary Report				●										
4	Project Work				■	■	■	■							
	-Selection of Process Tomography technique														
	-Selection of suitable components														
5	Submission of Progress Report								●						
6	Project work continue								■	■	■	■			
	-Circuit Design and Simulation														
	-Electrode Construction														
7	Submission of Interim Report Final Draft												●		
8	Oral Presentation													●	
9	Submission of Interim Report														●

No.	Detail/ Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Project Work Continue														
	- Circuit Construction														
	- C Programming Code														
2	Submission of Progress Report 1														
3	Project Work Continue														
	-Continuation of Circuit Construction														
4	Submission of Progress Report 2														
5	Project work continue														
	-Testing and Troubleshooting														
6	Submission of Dissertation Final Draft														
7	Oral Presentation														
8	Submission of Project Dissertation														

APPENDIX B

C PROGRAMMING CODES

```
#include <16F877.h>
#device ADC=10
#USE DELAY(CLOCK=4000000)
#FUSES XT,NOWDT,NOPROTECT,NOPUT,NOBROWNOUT,NOLVP
#USE RS232(baud=9600, parity=N, xmit=PIN_C6, rcv=PIN_C7, bits=8)

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);
  {
  while(1)
  {
   for(i=0;i<=0;i++)
   {
    output_d(i);
    {
     for(j=2;j<=6;j++)
     {
      output_c(j);
```

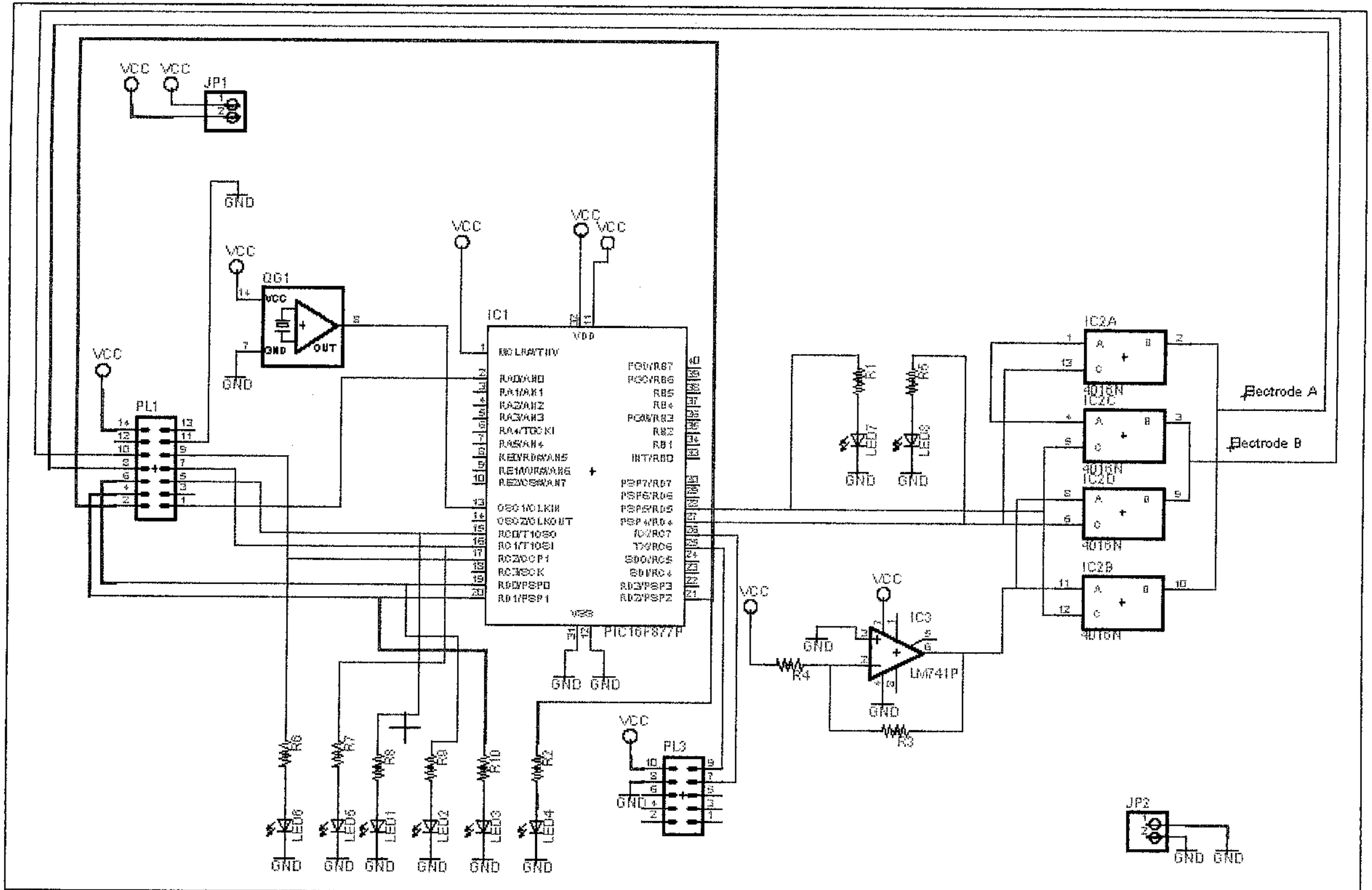
```
{
 output_high(PIN_D4);
 output_low(PIN_D5);

 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
 set_adc_channel(0);
 adcValue=read_adc(); //Get ADC reading

 while(1)


  {
  printf("\033[2J");  //clear hyperterminal screen
   {
  for(i=0;i<12;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("%u\n",adcValue);
printf("Pair Voltage %d:%f V\n",i,voltage);
delay_ms(500);

}
}
}

delay_ms(1000);
}
}
}
}

for(i=1;i<=5;i++)
{
output_d(i);
{
for(j=i+2;j<=7;j++)
{
output_c(j);
{
output_high(PIN_D4);
```

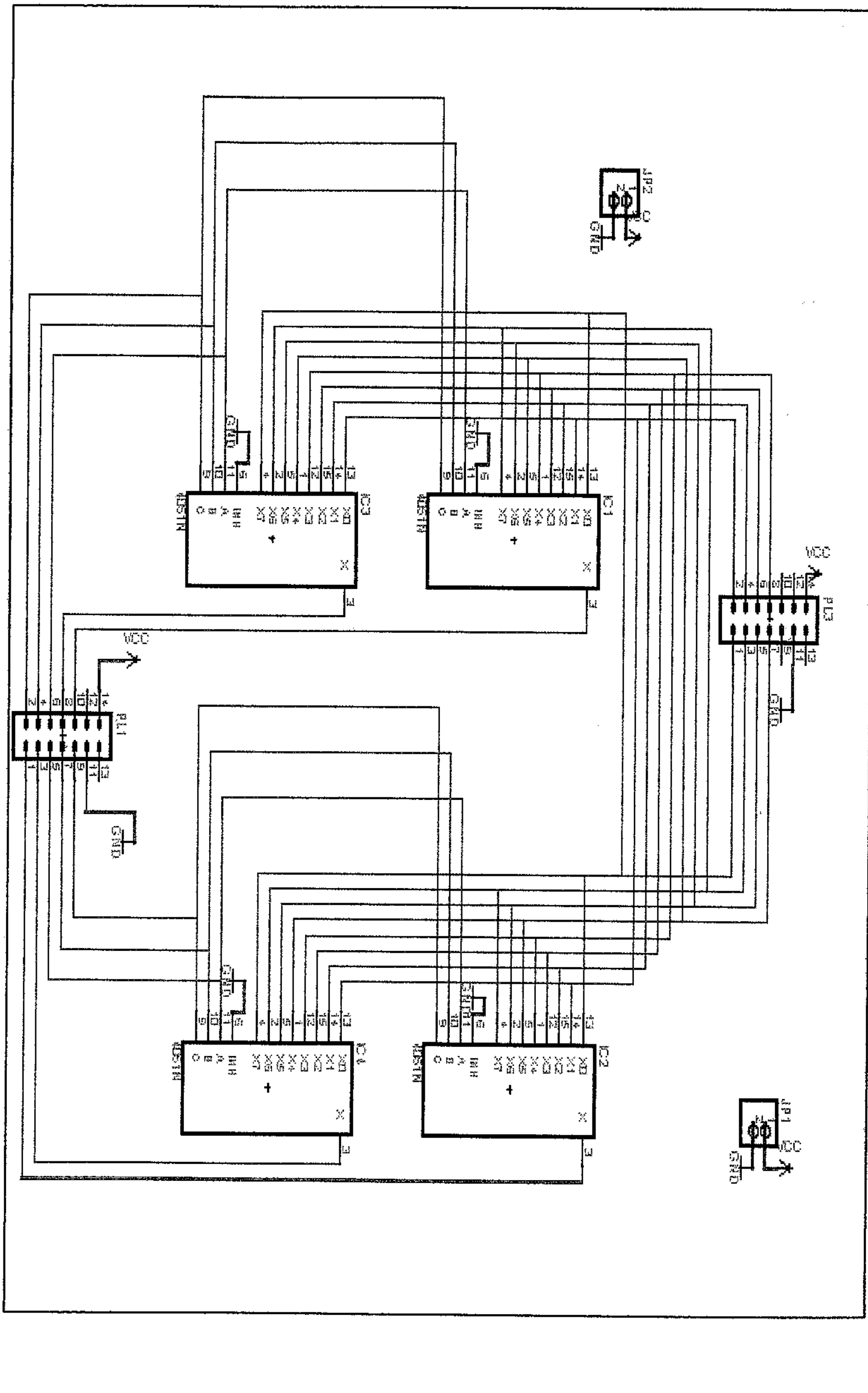
```
output_low(PIN_D5);

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
set_adc_channel(0);
adcValue=read_adc(); //Get ADC reading

while(1)


  {
  printf("\033[2J"); //clear hyperterminal screen
  {
  for(i=0;i<12;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("%u\n",adcValue);
        printf("Pair Voltage %d:%f V\n",i,voltage);
        delay_ms(500);

        }
       }
       }

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

APPENDIX C
SCHEMATIC DIAGRAM OF COMPLETE EIT CIRCUIT



JP1
QG1
IC1
PIC16F877P
PL1
PL3
IC3
LM741P
IC2A
IC2B
IC2C
IC2D
4016N
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
LED1
LED2
LED3
LED4
LED5
LED6
LED7
LED8
Electrode A
Electrode B
JP2
VCC
GND


VCC
GND

APPENDIX D
COMPONENT DATASHEETS

MC14051B, MC14052B, MC14053B

Analog Multiplexers/Demultiplexers

ON Semiconductor®

http://onsemi.com

The MC14051B, MC14052B, and MC14053B analog multiplexers ıre digitally−controlled analog switches. The MC14051B effectively mplements an SP8T solid state switch, the MC14052B a DP4T, and he MC14053B a Triple SPDT. All three devices feature low ON mpedance and very low OFF leakage current. Control of analog ignals up to the complete supply voltage range can be achieved.

·eatures

- Triple Diode Protection on Control Inputs
- Switch Function is Break Before Make
- Supply Voltage Range = 3.0 Vdc to 18 Vdc
- Analog Voltage Range ($V_{DD} - V_{EE}$) = 3.0 to 18 V
  Note: V_{EE} must be $\leq$ V_{SS}
- Linearized Transfer Characteristics
- Low−noise − 12 nV/$\sqrt{\text{Cycle}}$, f ≥ 1.0 kHz Typical
- Pin−for−Pin Replacement for CD4051, CD4052, and CD4053
- For 4PDT Switch, See MC14551B
- For Lower R_{ON}, Use the HC4051, HC4052, or HC4053 High−Speed CMOS Devices
- Pb−Free Packages are Available*

ɪAXIMUM RATINGS (Voltages Referenced to V_{SS})

Symbol	Parameter	Value	Unit
V_{DD}	DC Supply Voltage Range (Referenced to V_{EE}, $V_{SS} \geq V_{EE}$)	−0.5 to +18.0	V
V_{in}, V_{out}	Input or Output Voltage Range (DC or Transient) (Referenced to V_{SS} for Control Inputs and V_{EE} for Switch I/O)	−0.5 to V_{DD} + 0.5	V
I_{in}	Input Current (DC or Transient) per Control Pin	+10	mA
I_{SW}	Switch Through Current	±25	mA
P_D	Power Dissipation per Package (Note 1)	500	mW
T_A	Ambient Temperature Range	−55 to +125	°C
T_{stg}	Storage Temperature Range	−65 to +150	°C
T_L	Lead Temperature (8−Second Soldering)	260	°C

aximum ratings are those values beyond which device damage can occur. aximum ratings applied to the device are individual stress limit values (not ɪrmal operating conditions) and are not valid simultaneously. If these limits are ːceeded, device functional operation is not implied, damage may occur and liability may be affected.

Temperature Derating: Plastic "P and D/DW" Packages: − 7.0 mW/°C From 65°C To 125°C

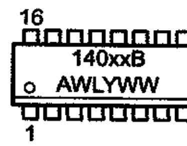
This device contains protection circuitry to guard against damage due to high ıtic voltages or electric fields. However, precautions must be taken to avoid plications of any voltage higher than maximum rated voltages to this ȷh−impedance circuit. For proper operation, V_{in} and V_{out} should be constrained to ɜ range $V_{SS} \leq (V_{in}$ or $V_{out}) \leq V_{DD}$.

Unused inputs must always be tied to an appropriate logic voltage level (e.g., either ꜱs, V_{EE} or V_{DD}). Unused outputs must be left open.

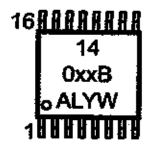
MARKING DIAGRAMS

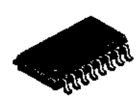
PDIP−16
P SUFFIX
CASE 648

SOIC−16
D SUFFIX
CASE 751B

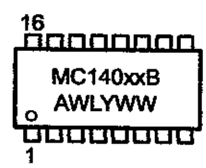


TSSOP−16
DT SUFFIX
CASE 948F





SOEIAJ−16
F SUFFIX
CASE 966



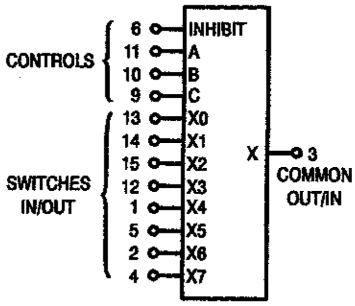
xx	=	Specific Device Code
A	=	Assembly Location
WL, L	=	Wafer Lot
YY, Y	=	Year
WW, W	=	Work Week

ORDERING INFORMATION

See detailed ordering and shipping information in the package dimensions section on page 9 of this data sheet.

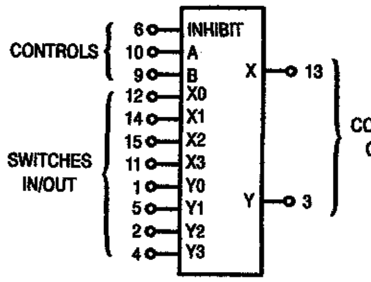
*For additional information on our Pb−Free strategy and soldering details, please download the ON Semiconductor Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

MC14051B
8−Channel Analog
Multiplexer/Demultiplexer



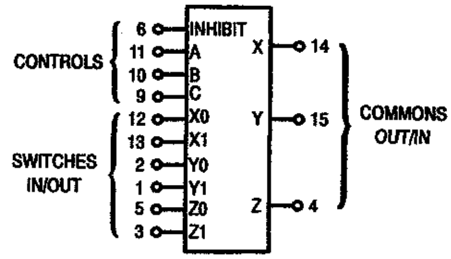
V_{DD} = PIN 16
V_{SS} = PIN 8
V_{EE} = PIN 7

MC14052B
Dual 4−Channel Analog
Multiplexer/Demultiplexer



V_{DD} = PIN 16
V_{SS} = PIN 8
V_{EE} = PIN 7

MC14053B
Triple 2−Channel Analog
Multiplexer/Demultiplexer

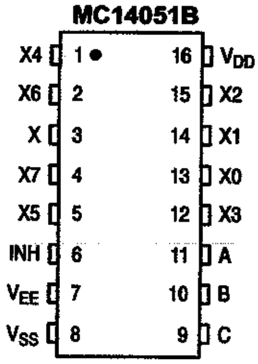


V_{DD} = PIN 16
V_{SS} = PIN 8
V_{EE} = PIN 7

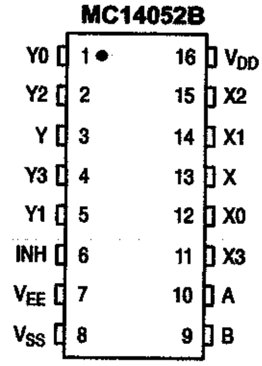
Note: Control Inputs referenced to V_{SS}, Analog Inputs and Outputs reference to V_{EE}. V_{EE} must be ≤ V_{SS}.

PIN ASSIGMENT

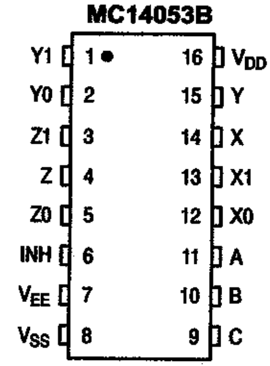
MC14051B



MC14052B



MC14053B



ELECTRICAL CHARACTERISTICS

Characteristic	Symbol	V_{DD}	Test Conditions	− 55°C		25°C			125°C		Unit
				Min	Max	Min	Typ (Note 2)	Max	Min	Max	
SUPPLY REQUIREMENTS (Voltages Referenced to V_{EE})											
Power Supply Voltage Range	V_{DD}	–	$V_{DD} - 3.0 \geq V_{SS} \geq V_{EE}$	3.0	18	3.0	–	18	3.0	18	V
Quiescent Current Per Package	I_{DD}	5.0 10 15	Control Inputs: $V_{in} = V_{SS}$ or V_{DD}, Switch I/O: $V_{EE} \leq V_{I/O} \leq V_{DD}$, and $\Delta V_{switch} \leq$ 500 mV (Note 3)	– – –	5.0 10 20	– – –	0.005 0.010 0.015	5.0 10 20	– – –	150 300 600	µA
Total Supply Current (Dynamic Plus Quiescent, Per Package	$I_{D(AV)}$	5.0 10 15	T_A = 25°C only (The channel component, $(V_{in} - V_{out})/R_{on}$, is not included.)		Typical		(0.07 µA/kHz) f + I_{DD} (0.20 µA/kHz) f + I_{DD} (0.36 µA/kHz) f + I_{DD}				µA
CONTROL INPUTS — INHIBIT, A, B, C (Voltages Referenced to V_{SS})											
Low−Level Input Voltage	V_{IL}	5.0 10 15	R_{on} = per spec, I_{off} = per spec	– – –	1.5 3.0 4.0	– – –	2.25 4.50 6.75	1.5 3.0 4.0	– – –	1.5 3.0 4.0	V
High−Level Input Voltage	V_{IH}	5.0 10 15	R_{on} = per spec, I_{off} = per spec	3.5 7.0 11	– – –	3.5 7.0 11	2.75 5.50 8.25	– – –	3.5 7.0 11	– – –	V
Input Leakage Current	I_{in}	15	V_{in} = 0 or V_{DD}	–	± 0.1	–	±0.00001	± 0.1	–	1.0	µA
Input Capacitance	C_{in}	–		–	–	–	5.0	7.5	–	–	pF
SWITCHES IN/OUT AND COMMONS OUT/IN — X, Y, Z (Voltages Referenced to V_{EE})											
Recommended Peak−to−Peak Voltage Into or Out of the Switch	$V_{I/O}$	–	Channel On or Off	0	V_{DD}	0	–	V_{DD}	0	V_{DD}	V_{PP}
Recommended Static or Dynamic Voltage Across the Switch (Note 3) (Figure 5)	ΔV_{switch}	–	Channel On	0	600	0	–	600	0	300	mV
Output Offset Voltage	V_{OO}	–	V_{in} = 0 V, No Load	–	–	–	10	–	–	–	µV
ON Resistance	R_{on}	5.0 10 15	$\Delta V_{switch} \leq$ 500 mV (Note 3) $V_{in} = V_{IL}$ or V_{IH} (Control), and V_{in} = 0 to V_{DD} (Switch)	– – –	800 400 220	– – –	250 120 80	1050 500 280	– – –	1200 520 300	Ω
ΔON Resistance Between Any Two Channels in the Same Package	ΔR_{on}	5.0 10 15		– – –	70 50 45	– – –	25 10 10	70 50 45	– – –	135 95 65	Ω
Off−Channel Leakage Current (Figure 10)	I_{off}	15	$V_{in} = V_{IL}$ or V_{IH} (Control) Channel to Channel or Any One Channel	–	± 100	–	± 0.05	± 100	–	±1000	nA
Capacitance, Switch I/O	$C_{I/O}$	–	Inhibit = V_{DD}	–	–	–	10	–	–	–	pF
Capacitance, Common O/I	$C_{O/I}$	–	Inhibit = V_{DD} (MC14051B) (MC14052B) (MC14053B)	 – – –	 – – –	 – – –	 60 32 17	 – – –	 – – –	 – – –	pF
Capacitance, Feedthrough (Channel Off)	$C_{I/O}$	– –	Pins Not Adjacent Pins Adjacent	– –	– –	– –	0.15 0.47	– –	– –	– –	pF

2. Data labeled "Typ" is not to be used for design purposes, but is intended as an indication of the IC's potential performance.
3. For voltage drops across the switch (ΔV_{switch}) > 600 mV (> 300 mV at high temperature), excessive V_{DD} current may be drawn, i.e. the current out of the switch may contain both V_{DD} and switch input components. The reliability of the device will be unaffected unless the Maximum Ratings are exceeded. (See first page of this data sheet.)

ELECTRICAL CHARACTERISTICS (Note 4) (C_L = 50 pF, T_A = 25°C) ($V_{EE} \le V_{SS}$ unless otherwise indicated)

Characteristic	Symbol	$V_{DD} - V_{EE}$ Vdc	Typ (Note 5) All Types	Max	Unit
Propagation Delay Times (Figure 6)	t_{PLH}, t_{PHL}				ns
Switch Input to Switch Output (R_L = 10 kΩ)					
MC14051					
t_{PLH}, t_{PHL} = (0.17 ns/pF) C_L + 26.5 ns		5.0	35	90	
t_{PLH}, t_{PHL} = (0.08 ns/pF) C_L + 11 ns		10	15	40	
t_{PLH}, t_{PHL} = (0.06 ns/pF) C_L + 9.0 ns		15	12	30	
MC14052					ns
t_{PLH}, t_{PHL} = (0.17 ns/pF) C_L + 21.5 ns		5.0	30	75	
t_{PLH}, t_{PHL} = (0.08 ns/pF) C_L + 8.0 ns		10	12	30	
t_{PLH}, t_{PHL} = (0.06 ns/pF) C_L + 7.0 ns		15	10	25	
MC14053					ns
t_{PLH}, t_{PHL} = (0.17 ns/pF) C_L + 16.5 ns		5.0	25	65	
t_{PLH}, t_{PHL} = (0.08 ns/pF) C_L + 4.0 ns		10	8.0	20	
t_{PLH}, t_{PHL} = (0.06 ns/pF) C_L + 3.0 ns		15	6.0	15	
Inhibit to Output (R_L = 10 kΩ, $V_{EE} = V_{SS}$) Output "1" or "0" to High Impedance, or High Impedance to "1" or "0" Level	t_{PHZ}, t_{PLZ}, t_{PZH}, t_{PZL}				ns
MC14051B		5.0	350	700	
		10	170	340	
		15	140	280	
MC14052B		5.0	300	600	ns
		10	155	310	
		15	125	250	
MC14053B		5.0	275	550	ns
		10	140	280	
		15	110	220	
Control Input to Output (R_L = 10 kΩ, $V_{EE} = V_{SS}$)	t_{PLH}, t_{PHL}				ns
MC14051B		5.0	360	720	
		10	160	320	
		15	120	240	
MC14052B		5.0	325	650	ns
		10	130	260	
		15	90	180	
MC14053B		5.0	300	600	ns
		10	120	240	
		15	80	160	
Second Harmonic Distortion (R_L = 10KΩ, f = 1 kHz) V_{in} = 5 V_{PP}	–	10	0.07	–	%
Bandwidth (Figure 7) (R_L = 1 kΩ, V_{in} = 1/2 ($V_{DD}-V_{EE}$) p–p, C_L = 50pF 20 Log (V_{out}/V_{in}) = – 3 dB)	BW	10	17	–	MHz
Off Channel Feedthrough Attenuation (Figure 7) R_L = 1KΩ, V_{in} = 1/2 ($V_{DD} - V_{EE}$) p–p; f_{in} = 4.5 MHz — MC14051B; f_{in} = 30 MHz — MC14052B; f_{in} = 55 MHz — MC14053B	–	10	– 50	–	dB
Channel Separation (Figure 8) (R_L = 1 kΩ, V_{in} = 1/2 ($V_{DD}-V_{EE}$) p–p, f_{in} = 3.0 MHz	–	10	– 50	–	dB
Crosstalk, Control Input to Common O/I (Figure 9) (R_1 = 1 kΩ, R_L = 10 kΩ Control $t_{TLH} = t_{THL}$ = 20 ns, Inhibit = V_{SS})	–	10	75	–	mV

The formulas given are for the typical characteristics only at 25°C.
Data labelled "Typ" is not lo be used for design purposes but In intended as an indication of the IC's potential performance.

LM741

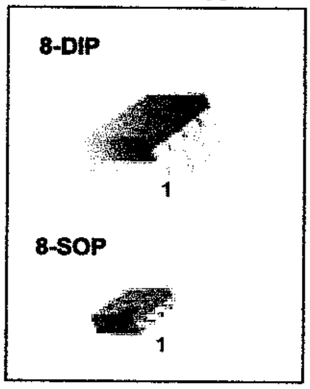
Single Operational Amplifier

Features

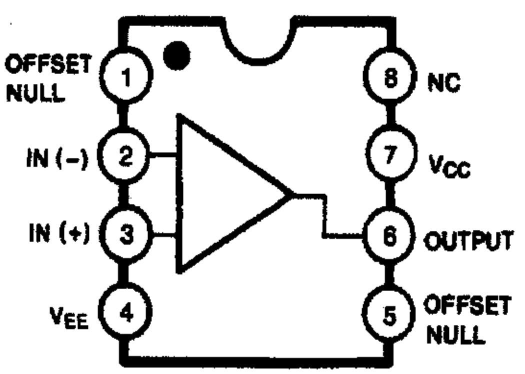
- Short circuit protection
- Excellent temperature stability
- Internal frequency compensation
- High Input voltage range
- Null of offset

Description

The LM741 series are general purpose operational amplifiers. It is intended for a wide range of analog applications. The high gain and wide range of operating voltage provide superior performance in intergrator, summing amplifier, and general feedback applications.

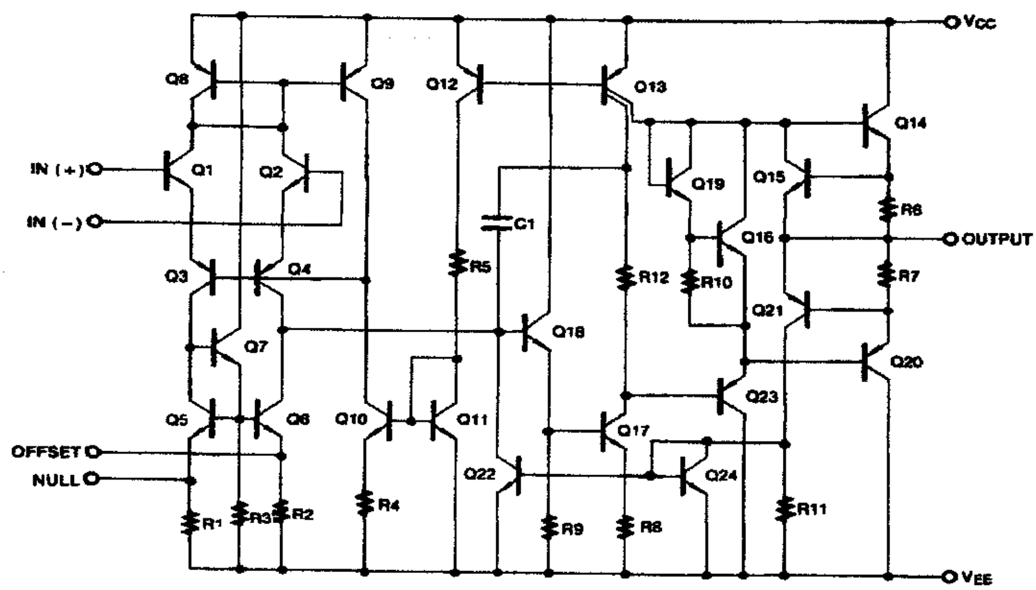


Internal Block Diagram



Rev. 1.0.1

Schematic Diagram



Absolute Maximum Ratings (T_A = 25°C)

Parameter	Symbol	Value	Unit
Supply Voltage	V_{CC}	±18	V
Differential Input Voltage	$V_{I(DIFF)}$	30	V
Input Voltage	V_I	±15	V
Output Short Circuit Duration	-	Indefinite	-
Power Dissipation	P_D	500	mW
Operating Temperature Range LM741C LM741I	T_{OPR}	0 ~ + 70 -40 ~ +85	°C
Storage Temperature Range	T_{STG}	-65 ~ + 150	°C

4323; Rev 11; 2/03

MAXIM

+5V-Powered, Multichannel RS-232 Drivers/Receivers

MAX220–MAX249

General Description

ɜ MAX220–MAX249 family of line drivers/receivers is ɜnded for all EIA/TIA-232E and V.28/V.24 communicaɪs interfaces, particularly applications where ±12V is available.

ɜse parts are especially useful in battery-powered sysɪs, since their low-power shutdown mode reduces wer dissipation to less than 5μW. The MAX225, ⟨X233, MAX235, and MAX245/MAX246/MAX247 use external components and are recommended for appliions where printed circuit board space is critical.

Applications

Portable Computers

Low-Power Modems

Interface Translation

Battery-Powered RS-232 Systems

Multidrop RS-232 Networks

Features

Superior to Bipolar

- **Operate from Single +5V Power Supply (+5V and +12V—MAX231/MAX239)**
- **Low-Power Receive Mode in Shutdown (MAX223/MAX242)**
- **Meet All EIA/TIA-232E and V.28 Specifications**
- **Multiple Drivers and Receivers**
- **3-State Driver and Receiver Outputs**
- **Open-Line Detection (MAX243)**

Ordering Information

PART	TEMP RANGE	PIN-PACKAGE
MAX220CPE	0°C to +70°C	16 Plastic DIP
MAX220CSE	0°C to +70°C	16 Narrow SO
MAX220CWE	0°C to +70°C	16 Wide SO
MAX220C/D	0°C to +70°C	Dice*
MAX220EPE	-40°C to +85°C	16 Plastic DIP
MAX220ESE	-40°C to +85°C	16 Narrow SO
MAX220EWE	-40°C to +85°C	16 Wide SO
MAX220EJE	-40°C to +85°C	16 CERDIP
MAX220MJE	-55°C to +125°C	16 CERDIP

Ordering Information continued at end of data sheet.

**Contact factory for dice specifications.*

Selection Table

t mber	Power Supply (V)	No. of RS-232 Drivers/Rx	No. of Ext. Caps	Nominal Cap. Value (μF)	SHDN & Three-State	Rx Active in SHDN	Data Rate (kbps)	Features
X220	+5	2/2	4	0.1	No	—	120	Ultra-low-power, industry-standard pinout
X222	+5	2/2	4	0.1	Yes	—	200	Low-power shutdown
X223 (MAX213)	+5	4/5	4	1.0 (0.1)	Yes	✔	120	MAX241 and receivers active in shutdown
X225	+5	5/5	0	—	Yes	✔	120	Available in SO
X230 (MAX200)	+5	5/0	4	1.0 (0.1)	Yes	—	120	5 drivers with shutdown
X231 (MAX201)	+5 and +7.5 to +13.2	2/2	2	1.0 (0.1)	No	—	120	Standard +5/+12V or battery supplies; same functions as MAX232
X232 (MAX202)	+5	2/2	4	1.0 (0.1)	No	—	120 (64)	Industry standard
X232A	+5	2/2	4	0.1	No	—	200	Higher slew rate, small caps
X233 (MAX203)	+5	2/2	0	—	No	—	120	No external caps
X233A	+5	2/2	0	—	No	—	200	No external caps, high slew rate
X234 (MAX204)	+5	4/0	4	1.0 (0.1)	No	—	120	Replaces 1488
X235 (MAX205)	+5	5/5	0	—	Yes	—	120	No external caps
X236 (MAX206)	+5	4/3	4	1.0 (0.1)	Yes	—	120	Shutdown, three state
X237 (MAX207)	+5	5/3	4	1.0 (0.1)	No	—	120	Complements IBM PC serial port
X238 (MAX208)	+5	4/4	4	1.0 (0.1)	No	—	120	Replaces 1488 and 1489
X239 (MAX209)	+5 and +7.5 to +13.2	3/5	2	1.0 (0.1)	No	—	120	Standard +5/+12V or battery supplies; single-package solution for IBM PC serial port
X240	+5	5/5	4	1.0	Yes	—	120	DIP or flatpack package
X241 (MAX211)	+5	4/5	4	1.0 (0.1)	Yes	—	120	Complete IBM PC serial port
X242	+5	2/2	4	0.1	Yes	✔	200	Separate shutdown and enable
X243	+5	2/2	4	0.1	No	—	200	Open-line detection simplifies cabling
X244	+5	8/10	4	1.0	No	—	120	High slew rate
X245	+5	8/10	0	—	Yes	✔	120	High slew rate, int. caps, two shutdown modes
X246	+5	8/10	0	—	Yes	✔	120	High slew rate, int. caps, three shutdown modes
X247	+5	8/9	0	—	Yes	✔	120	High slew rate, int. caps, nine operating modes
X248	+5	8/8	4	1.0	Yes	✔	120	High slew rate, selective half-chip enables
X249	+5	6/10	4	1.0	Yes	✔	120	Available in quad flatpack package

ɾ pricing, delivery, and ordering information, please contact Maxim/Dallas Direct! at ...-...-4642, or visit Maxim's website at www.maxim-ic.com.

5V-Powered, Multichannel RS-232 Drivers/Receivers

BSOLUTE MAXIMUM RATINGS—MAX220/222/232A/233A/242/243

pply Voltage (V_{CC}) ....-0.3V to +6V
ut Voltages
N..-0.3V to (V_{CC} - 0.3V)
N (Except MAX220) ....±30V
N (MAX220)..±25V
OUT (Except MAX220) (Note 1) ....±15V
OUT (MAX220)..±13.2V
tput Voltages
OUT...±15V
OUT...-0.3V to (V_{CC} + 0.3V)
ver/Receiver Output Short Circuited to GND.........Continuous
ntinuous Power Dissipation (T_A = +70°C)
-Pin Plastic DIP (derate 10.53mW/°C above +70°C)....842mW
-Pin Plastic DIP (derate 11.11mW/°C above +70°C)....889mW
20-Pin Plastic DIP (derate 8.00mW/°C above +70°C) ..440mW
16-Pin Narrow SO (derate 8.70mW/°C above +70°C)...696mW
16-Pin Wide SO (derate 9.52mW/°C above +70°C)......762mW
18-Pin Wide SO (derate 9.52mW/°C above +70°C)......762mW
20-Pin Wide SO (derate 10.00mW/°C above +70°C)....800mW
20-Pin SSOP (derate 8.00mW/°C above +70°C) 640mW
16-Pin CERDIP (derate 10.00mW/°C above +70°C).....800mW
18-Pin CERDIP (derate 10.53mW/°C above +70°C).....842mW
Operating Temperature Ranges
MAX2_ _AC_ _, MAX2_ _C_ _...........................0°C to +70°C
MAX2_ _AE_ _, MAX2_ _E_ _ ....-40°C to +85°C
MAX2_ _AM_ _, MAX2_ _M_ _.......................-55°C to +125°C
Storage Temperature Range ....-65°C to +160°C
Lead Temperature (soldering, 10s) ....+300°C

te 1: Input voltage measured with T_{OUT} in high-impedance state, $\overline{SHDN}$ or V_{CC} = 0V.
te 2: For the MAX220, V+ and V- can have a maximum magnitude of 7V, but their absolute difference cannot exceed 13V.

esses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional eration of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to solute maximum rating conditions for extended periods may affect device reliability.

LECTRICAL CHARACTERISTICS—MAX220/222/232A/233A/242/243

CC = +5V ±10%, C1–C4 = 0.1μF, MAX220, C1 = 0.047μF, C2–C4 = 0.33μF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted.)

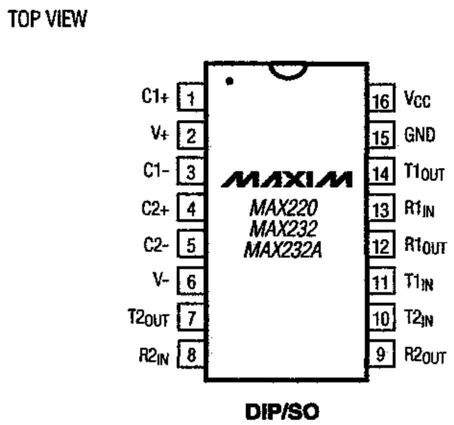
PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
S-232 TRANSMITTERS					
utput Voltage Swing	All transmitter outputs loaded with 3kΩ to GND	±5	±8		V
put Logic Threshold Low			1.4	0.8	V
put Logic Threshold High	All devices except MAX220	2	1.4		V
	MAX220: V_{CC} = 5.0V	2.4			
ogic Pull-Up/Input Current	All except MAX220, normal operation		5	40	μA
	$\overline{SHDN}$ = 0V, MAX222/242, shutdown, MAX220		±0.01	±1	
utput Leakage Current	V_{CC} = 5.5V, $\overline{SHDN}$ = 0V, V_{OUT} = ±15V, MAX222/242		±0.01	±10	μA
	V_{CC} = $\overline{SHDN}$ = 0V, V_{OUT} = ±15V		±0.01	±10	
ata Rate			200	116	kbps
ansmitter Output Resistance	V_{CC} = V+ = V- = 0V, V_{OUT} = ±2V	300	10M		Ω
utput Short-Circuit Current	V_{OUT} = 0V	±7	±22		mA
S-232 RECEIVERS					
S-232 Input Voltage Operating Range				±30	V
S-232 Input Threshold Low	V_{CC} = 5V; All except MAX243 $R2_{IN}$	0.8	1.3		V
	V_{CC} = 5V; MAX243 $R2_{IN}$ (Note 2)	-3			
S-232 Input Threshold High	V_{CC} = 5V; All except MAX243 $R2_{IN}$		1.8	2.4	V
	V_{CC} = 5V; MAX243 $R2_{IN}$ (Note 2)		-0.5	-0.1	
S-232 Input Hysteresis	All except MAX243, V_{CC} = 5V, no hysteresis in shdn.	0.2	0.5	1	V
	MAX243		1		
S-232 Input Resistance		3	5	7	kΩ
TL/CMOS Output Voltage Low	I_{OUT} = 3.2mA		0.2	0.4	V
TL/CMOS Output Voltage High	I_{OUT} = -1.0mA	3.5	V_{CC} - 0.2		V
TL/CMOS Output Short-Circuit Current	Sourcing V_{OUT} = GND	-2	-10		mA
	Shrinking V_{OUT} = V_{CC}	10	30		

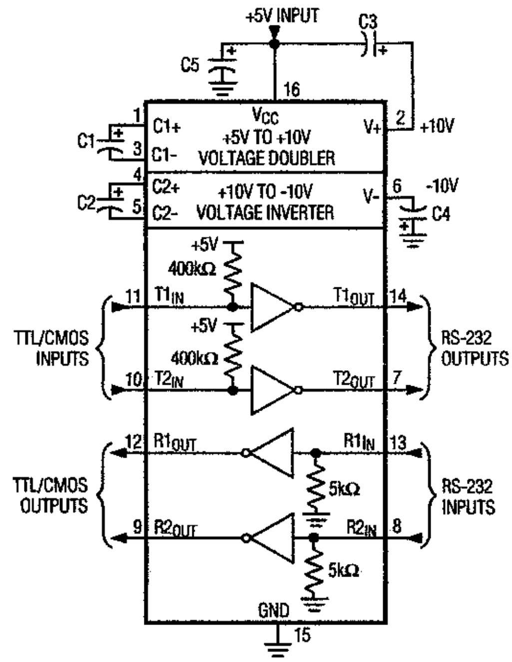
LECTRICAL CHARACTERISTICS—MAX220/222/232A/233A/242/243 (continued)

$_{CC}$ = +5V ±10%, C1–C4 = 0.1µF, MAX220, C1 = 0.047µF, C2–C4 = 0.33µF, T_A = T_{MIN} to T_{MAX}, unless otherwise noted.)

PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
TL/CMOS Output Leakage Current	$\overline{SHDN}$ = V_{CC} or $\overline{EN}$ = V_{CC} ($\overline{SHDN}$ = 0V for MAX222), 0V ≤ V_{OUT} ≤ V_{CC}			±0.05	±10	µA
$\overline{N}$ Input Threshold Low	MAX242			1.4	0.8	V
$\overline{N}$ Input Threshold High	MAX242		2.0	1.4		V
'perating Supply Voltage			4.5		5.5	V
$_{CC}$ Supply Current ($\overline{SHDN}$ = V_{CC}), igures 5, 6, 11, 19	No load	MAX220		0.5	2	mA
		MAX222/232A/233A/242/243		4	10	
	3kΩ load both inputs	MAX220		12		
		MAX222/232A/233A/242/243		15		
hutdown Supply Current	MAX222/242	T_A = +25°C		0.1	10	µA
		T_A = 0°C to +70°C		2	50	
		T_A = -40°C to +85°C		2	50	
		T_A = -55°C to +125°C		35	100	
$\overline{HDN}$ Input Leakage Current	MAX222/242				±1	µA
$\overline{HDN}$ Threshold Low	MAX222/242			1.4	0.8	V
$\overline{HDN}$ Threshold High	MAX222/242		2.0	1.4		V
'ansition Slew Rate	C_L = 50pF to 2500pF, R_L = 3kΩ to 7kΩ, V_{CC} = 5V, T_A = +25°C, measured from +3V to -3V or -3V to +3V	MAX222/232A/233A/242/243	6	12	30	V/µs
		MAX220	1.5	3	30	
'ansmitter Propagation Delay .L to RS-232 (Normal Operation), gure 1	t_{PHLT}	MAX222/232A/233A/242/243		1.3	3.5	µs
		MAX220		4	10	
	t_{PLHT}	MAX222/232A/233A/242/243		1.5	3.5	
		MAX220		5	10	
eceiver Propagation Delay S-232 to TLL (Normal Operation), gure 2	t_{PHLR}	MAX222/232A/233A/242/243		0.5	1	µs
		MAX220		0.6	3	
	t_{PLHR}	MAX222/232A/233A/242/243		0.6	1	
		MAX220		0.8	3	
eceiver Propagation Delay S-232 to TLL (Shutdown), Figure 2	t_{PHLS}	MAX242		0.5	10	µs
	t_{PLHS}	MAX242		2.5	10	
eceiver-Output Enable Time, Figure 3	t_{ER}	MAX242		125	500	ns
eceiver-Output Disable Time, Figure 3	t_{DR}	MAX242		160	500	ns
ansmitter-Output Enable Time $\overline{HDN}$ Goes High), Figure 4	t_{ET}	MAX222/242, 0.1µF caps (includes charge-pump start-up)		250		µs
ansmitter-Output Disable Time $\overline{HDN}$ Goes Low), Figure 4	t_{DT}	MAX222/242, 0.1µF caps		600		ns
ansmitter + to - Propagation elay Difference (Normal Operation)	t_{PHLT} - t_{PLHT}	MAX222/232A/233A/242/243		300		ns
		MAX220		2000		
eceiver + to - Propagation elay Difference (Normal Operation)	t_{PHLR} - t_{PLHR}	MAX222/232A/233A/242/243		100		ns
		MAX220		225		

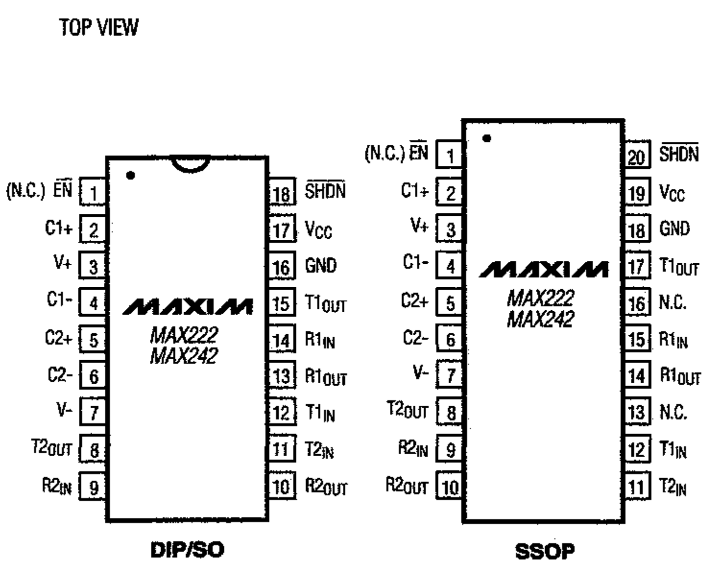
te 3: MAX243 $R2_{OUT}$ is guaranteed to be low when $R2_{IN}$ is ≥ 0V or is floating.

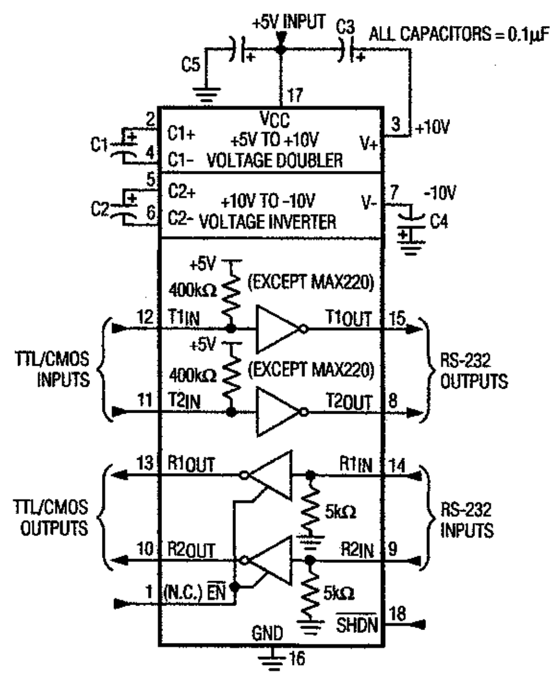




CAPACITANCE (µF)					
DEVICE	C1	C2	C3	C4	C5
MAX220	4.7	4.7	10	10	4.7
MAX232	1.0	1.0	1.0	1.0	1.0
MAX232A	0.1	0.1	0.1	0.1	0.1

gure 5. *MAX220/MAX232/MAX232A Pin Configuration and Typical Operating Circuit*





( ) ARE FOR MAX222 ONLY.
PIN NUMBERS IN TYPICAL OPERATING CIRCUIT ARE FOR DIP/SO PACKAGES ONLY.

gure 6. *MAX222/MAX242 Pin Configurations and Typical Operating Circuit*

MICROCHIP PIC16F87X

28/40-Pin 8-Bit CMOS FLASH Microcontrollers

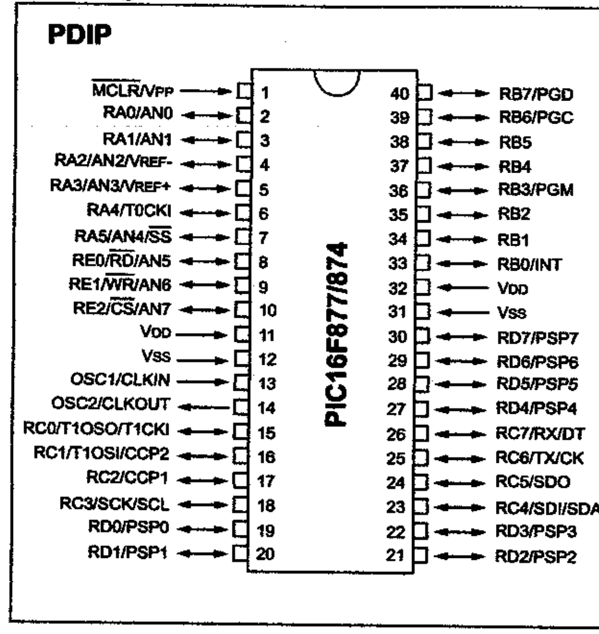
Devices Included in this Data Sheet:

- PIC16F873
- PIC16F874
- PIC16F876
- PIC16F877

Microcontroller Core Features:

- High performance RISC CPU
- Only 35 single word instructions to learn
- All single cycle instructions except for program branches which are two cycle
- Operating speed: DC - 20 MHz clock input
  DC - 200 ns instruction cycle
- Up to 8K x 14 words of FLASH Program Memory,
  Up to 368 x 8 bytes of Data Memory (RAM)
  Up to 256 x 8 bytes of EEPROM Data Memory
- Pinout compatible to the PIC16C73B/74B/76/77
- Interrupt capability (up to 14 sources)
- Eight level deep hardware stack
- Direct, indirect and relative addressing modes
- Power-on Reset (POR)
- Power-up Timer (PWRT) and Oscillator Start-up Timer (OST)
- Watchdog Timer (WDT) with its own on-chip RC oscillator for reliable operation
- Programmable code protection
- Power saving SLEEP mode
- Selectable oscillator options
- Low power, high speed CMOS FLASH/EEPROM technology
- Fully static design
- In-Circuit Serial Programming™ (ICSP) via two pins
- Single 5V In-Circuit Serial Programming capability
- In-Circuit Debugging via two pins
- Processor read/write access to program memory
- Wide operating voltage range: 2.0V to 5.5V
- High Sink/Source Current: 25 mA
- Commercial, Industrial and Extended temperature ranges
- Low-power consumption:
  - < 0.6 mA typical @ 3V, 4 MHz
  - 20 μA typical @ 3V, 32 kHz
  - < 1 μA typical standby current

Pin Diagram

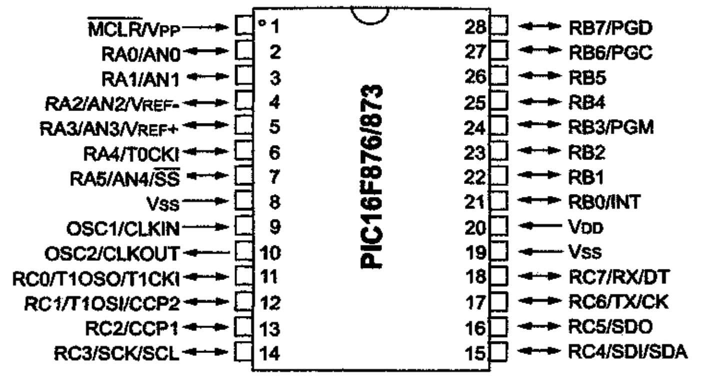


Peripheral Features:

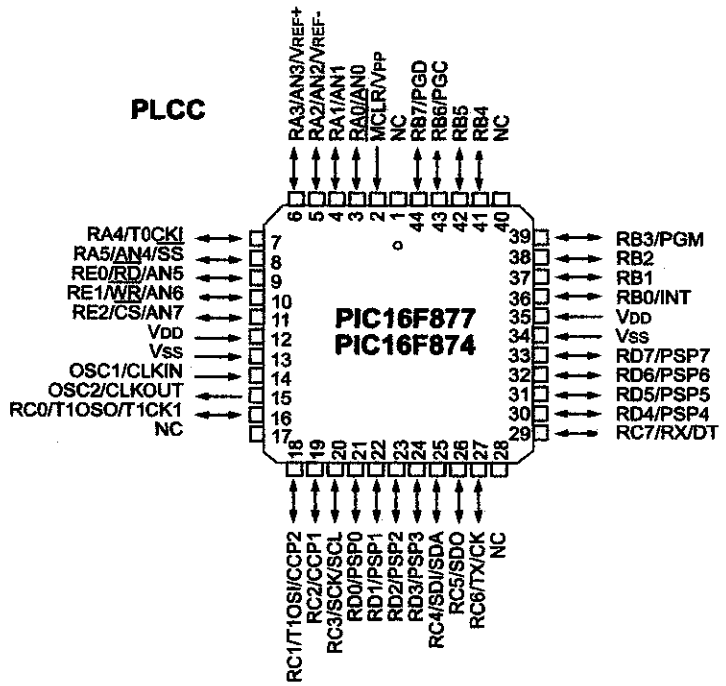
- Timer0: 8-bit timer/counter with 8-bit prescaler
- Timer1: 16-bit timer/counter with prescaler, can be incremented during SLEEP via external crystal/clock
- Timer2: 8-bit timer/counter with 8-bit period register, prescaler and postscaler
- Two Capture, Compare, PWM modules
  - Capture is 16-bit, max. resolution is 12.5 ns
  - Compare is 16-bit, max. resolution is 200 ns
  - PWM max. resolution is 10-bit
- 10-bit multi-channel Analog-to-Digital converter
- Synchronous Serial Port (SSP) with SPI™ (Master mode) and I²C™ (Master/Slave)
- Universal Synchronous Asynchronous Receiver Transmitter (USART/SCI) with 9-bit address detection
- Parallel Slave Port (PSP) 8-bits wide, with external RD, WR and CS controls (40/44-pin only)
- Brown-out detection circuitry for Brown-out Reset (BOR)

Pin Diagrams

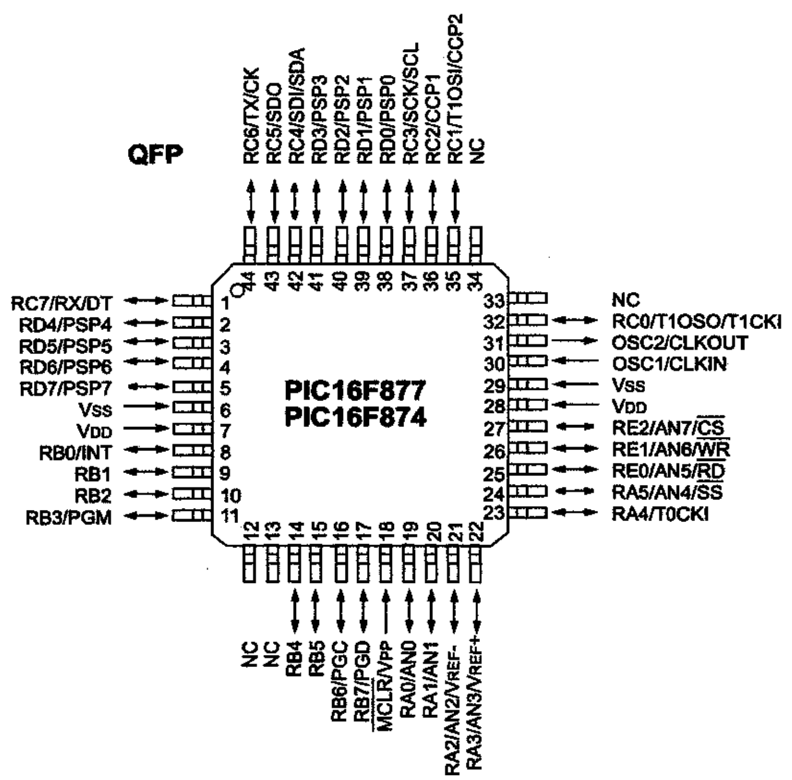
PDIP, SOIC



PLCC



QFP



Key Features PICmicro™ Mid-Range Reference Manual (DS33023)	PIC16F873	PIC16F874	PIC16F876	PIC16F877
Operating Frequency	DC - 20 MHz	DC - 20 MHz	DC - 20 MHz	DC - 20 MHz
RESETS (and Delays)	POR, BOR (PWRT, OST)	POR, BOR (PWRT, OST)	POR, BOR (PWRT, OST)	POR, BOR (PWRT, OST)
FLASH Program Memory (14-bit words)	4K	4K	8K	8K
Data Memory (bytes)	192	192	368	368
EEPROM Data Memory	128	128	256	256
Interrupts	13	14	13	14
I/O Ports	Ports A,B,C	Ports A,B,C,D,E	Ports A,B,C	Ports A,B,C,D,E
Timers	3	3	3	3
Capture/Compare/PWM Modules	2	2	2	2
Serial Communications	MSSP, USART	MSSP, USART	MSSP, USART	MSSP, USART
Parallel Communications	—	PSP	—	PSP
10-bit Analog-to-Digital Module	5 input channels	8 input channels	5 input channels	8 input channels
Instruction Set	35 instructions	35 instructions	35 instructions	35 instructions

TABLE 1-1: PIC16F873 AND PIC16F876 PINOUT DESCRIPTION

Pin Name	DIP Pin#	SOIC Pin#	I/O/P Type	Buffer Type	Description
OSC1/CLKIN	9	9	I	ST/CMOS(3)	Oscillator crystal input/external clock source input.
OSC2/CLKOUT	10	10	O	—	Oscillator crystal output. Connects to crystal or resonator in crystal oscillator mode. In RC mode, the OSC2 pin outputs CLKOUT which has 1/4 the frequency of OSC1, and denotes the instruction cycle rate.
$\overline{\text{MCLR}}$/VPP	1	1	I/P	ST	Master Clear (Reset) input or programming voltage input. This pin is an active low RESET to the device.
					PORTA is a bi-directional I/O port.
RA0/AN0	2	2	I/O	TTL	RA0 can also be analog input0.
RA1/AN1	3	3	I/O	TTL	RA1 can also be analog input1.
RA2/AN2/VREF-	4	4	I/O	TTL	RA2 can also be analog input2 or negative analog reference voltage.
RA3/AN3/VREF+	5	5	I/O	TTL	RA3 can also be analog input3 or positive analog reference voltage.
RA4/T0CKI	6	6	I/O	ST	RA4 can also be the clock input to the Timer0 module. Output is open drain type.
RA5/$\overline{\text{SS}}$/AN4	7	7	I/O	TTL	RA5 can also be analog input4 or the slave select for the synchronous serial port.
					PORTB is a bi-directional I/O port. PORTB can be software programmed for internal weak pull-up on all inputs.
RB0/INT	21	21	I/O	TTL/ST(1)	RB0 can also be the external interrupt pin.
RB1	22	22	I/O	TTL	
RB2	23	23	I/O	TTL	
RB3/PGM	24	24	I/O	TTL	RB3 can also be the low voltage programming input.
RB4	25	25	I/O	TTL	Interrupt-on-change pin.
RB5	26	26	I/O	TTL	Interrupt-on-change pin.
RB6/PGC	27	27	I/O	TTL/ST(2)	Interrupt-on-change pin or In-Circuit Debugger pin. Serial programming clock.
RB7/PGD	28	28	I/O	TTL/ST(2)	Interrupt-on-change pin or In-Circuit Debugger pin. Serial programming data.
					PORTC is a bi-directional I/O port.
RC0/T1OSO/T1CKI	11	11	I/O	ST	RC0 can also be the Timer1 oscillator output or Timer1 clock input.
RC1/T1OSI/CCP2	12	12	I/O	ST	RC1 can also be the Timer1 oscillator input or Capture2 input/Compare2 output/PWM2 output.
RC2/CCP1	13	13	I/O	ST	RC2 can also be the Capture1 input/Compare1 output/ PWM1 output.
RC3/SCK/SCL	14	14	I/O	ST	RC3 can also be the synchronous serial clock input/output for both SPI and I^2C modes.
RC4/SDI/SDA	15	15	I/O	ST	RC4 can also be the SPI Data In (SPI mode) or data I/O (I^2C mode).
RC5/SDO	16	16	I/O	ST	RC5 can also be the SPI Data Out (SPI mode).
RC6/TX/CK	17	17	I/O	ST	RC6 can also be the USART Asynchronous Transmit or Synchronous Clock.
RC7/RX/DT	18	18	I/O	ST	RC7 can also be the USART Asynchronous Receive or Synchronous Data.
VSS	8, 19	8, 19	P	—	Ground reference for logic and I/O pins.
VDD	20	20	P	—	Positive supply for logic and I/O pins.

Legend: I = input O = output I/O = input/output P = power
— = Not used TTL = TTL input ST = Schmitt Trigger input

Note 1: This buffer is a Schmitt Trigger input when configured as the external interrupt.
2: This buffer is a Schmitt Trigger input when used in Serial Programming mode.
3: This buffer is a Schmitt Trigger input when configured in RC oscillator mode and a CMOS input otherwise.

TABLE 1-2: PIC16F874 AND PIC16F877 PINOUT DESCRIPTION

Pin Name	DIP Pin#	PLCC Pin#	QFP Pin#	I/O/P Type	Buffer Type	Description
OSC1/CLKIN	13	14	30	I	ST/CMOS(4)	Oscillator crystal input/external clock source input.
OSC2/CLKOUT	14	15	31	O	—	Oscillator crystal output. Connects to crystal or resonator in crystal oscillator mode. In RC mode, OSC2 pin outputs CLKOUT which has 1/4 the frequency of OSC1, and denotes the instruction cycle rate.
$\overline{\text{MCLR}}$/VPP	1	2	18	I/P	ST	Master Clear (Reset) input or programming voltage input. This pin is an active low RESET to the device.
						PORTA is a bi-directional I/O port.
RA0/AN0	2	3	19	I/O	TTL	RA0 can also be analog input0.
RA1/AN1	3	4	20	I/O	TTL	RA1 can also be analog input1.
RA2/AN2/VREF-	4	5	21	I/O	TTL	RA2 can also be analog input2 or negative analog reference voltage.
RA3/AN3/VREF+	5	6	22	I/O	TTL	RA3 can also be analog input3 or positive analog reference voltage.
RA4/T0CKI	6	7	23	I/O	ST	RA4 can also be the clock input to the Timer0 timer/counter. Output is open drain type.
RA5/$\overline{\text{SS}}$/AN4	7	8	24	I/O	TTL	RA5 can also be analog input4 or the slave select for the synchronous serial port.
						PORTB is a bi-directional I/O port. PORTB can be software programmed for internal weak pull-up on all inputs.
RB0/INT	33	36	8	I/O	TTL/ST(1)	RB0 can also be the external interrupt pin.
RB1	34	37	9	I/O	TTL	
RB2	35	38	10	I/O	TTL	
RB3/PGM	36	39	11	I/O	TTL	RB3 can also be the low voltage programming input.
RB4	37	41	14	I/O	TTL	Interrupt-on-change pin.
RB5	38	42	15	I/O	TTL	Interrupt-on-change pin.
RB6/PGC	39	43	16	I/O	TTL/ST(2)	Interrupt-on-change pin or In-Circuit Debugger pin. Serial programming clock.
RB7/PGD	40	44	17	I/O	TTL/ST(2)	Interrupt-on-change pin or In-Circuit Debugger pin. Serial programming data.

Legend: I = input O = output I/O = input/output P = power
— = Not used TTL = TTL input ST = Schmitt Trigger input

Note 1: This buffer is a Schmitt Trigger input when configured as an external interrupt.
2: This buffer is a Schmitt Trigger input when used in Serial Programming mode.
3: This buffer is a Schmitt Trigger input when configured as general purpose I/O and a TTL input when used in the Parallel Slave Port mode (for interfacing to a microprocessor bus).
4: This buffer is a Schmitt Trigger input when configured in RC oscillator mode and a CMOS input otherwise.

TABLE 1-2: PIC16F874 AND PIC16F877 PINOUT DESCRIPTION (CONTINUED)

Pin Name	DIP Pin#	PLCC Pin#	QFP Pin#	I/O/P Type	Buffer Type	Description
						PORTC is a bi-directional I/O port.
RC0/T1OSO/T1CKI	15	16	32	I/O	ST	RC0 can also be the Timer1 oscillator output or a Timer1 clock input.
RC1/T1OSI/CCP2	16	18	35	I/O	ST	RC1 can also be the Timer1 oscillator input or Capture2 input/Compare2 output/PWM2 output.
RC2/CCP1	17	19	36	I/O	ST	RC2 can also be the Capture1 input/Compare1 output/PWM1 output.
RC3/SCK/SCL	18	20	37	I/O	ST	RC3 can also be the synchronous serial clock input/output for both SPI and I^2C modes.
RC4/SDI/SDA	23	25	42	I/O	ST	RC4 can also be the SPI Data In (SPI mode) or data I/O (I^2C mode).
RC5/SDO	24	26	43	I/O	ST	RC5 can also be the SPI Data Out (SPI mode).
RC6/TX/CK	25	27	44	I/O	ST	RC6 can also be the USART Asynchronous Transmit or Synchronous Clock.
RC7/RX/DT	26	29	1	I/O	ST	RC7 can also be the USART Asynchronous Receive or Synchronous Data.
						PORTD is a bi-directional I/O port or parallel slave port when interfacing to a microprocessor bus.
RD0/PSP0	19	21	38	I/O	ST/TTL(3)	
RD1/PSP1	20	22	39	I/O	ST/TTL(3)	
RD2/PSP2	21	23	40	I/O	ST/TTL(3)	
RD3/PSP3	22	24	41	I/O	ST/TTL(3)	
RD4/PSP4	27	30	2	I/O	ST/TTL(3)	
RD5/PSP5	28	31	3	I/O	ST/TTL(3)	
RD6/PSP6	29	32	4	I/O	ST/TTL(3)	
RD7/PSP7	30	33	5	I/O	ST/TTL(3)	
						PORTE is a bi-directional I/O port.
RE0/$\overline{RD}$/AN5	8	9	25	I/O	ST/TTL(3)	RE0 can also be read control for the parallel slave port, or analog input5.
RE1/$\overline{WR}$/AN6	9	10	26	I/O	ST/TTL(3)	RE1 can also be write control for the parallel slave port, or analog input6.
RE2/$\overline{CS}$/AN7	10	11	27	I/O	ST/TTL(3)	RE2 can also be select control for the parallel slave port, or analog input7.
VSS	12,31	13,34	6,29	P	—	Ground reference for logic and I/O pins.
VDD	11,32	12,35	7,28	P	—	Positive supply for logic and I/O pins.
NC	—	1,17,28, 40	12,13, 33,34		—	These pins are not internally connected. These pins should be left unconnected.

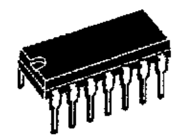
Legend: I = input O = output I/O = input/output P = power
— = Not used TTL = TTL input ST = Schmitt Trigger input

Note 1: This buffer is a Schmitt Trigger input when configured as an external interrupt.
2: This buffer is a Schmitt Trigger input when used in Serial Programming mode.
3: This buffer is a Schmitt Trigger input when configured as general purpose I/O and a TTL input when used in the Parallel Slave Port mode (for interfacing to a microprocessor bus).
4: This buffer is a Schmitt Trigger input when configured in RC oscillator mode and a CMOS input otherwise.

HCF4066B

QUAD BILATERAL SWITCH FOR TRANSMISSION OR MULTIPLEXING OF ANALOG OR DIGITAL SIGNALS

- 15V DIGITAL OR ± 7.5V PEAK TO PEAK SWITCHING
- 125Ω TYPICAL ON RESISTANCE FOR 15V OPERATION
- SWITCH ON RESISTANCE MATCHED TO WITHIN 5Ω TYP. OVER 15V SIGNAL INPUT RANGE
- ON RESISTANCE FLAT OVER FULL PEAK TO PEAK SIGNAL RANGE
- HIGH ON/OFF OUTPUT VOLTAGE RATIO : 65dB TYP. at f_{IS} = 10KHz, R_L = 10KΩ
- HIGH DEGREE OF LINEARITY : < 0.5% DISTORTION TYP. at f_{IS} = 1KHz, V_{IS} = 5 V_{pp}, V_{DD} - $V_{SS} \geq$ 10V, RL = 10KΩ
- EXTREMELY LOW OFF SWITCH LEAKAGE RESULTING IN VERY LOW OFFSET CURRENT AND HIGH EFFECTIVE OFF RESISTANCE : 10pA TYP. at V_{DD} - V_{SS} = 10V, T_{amb} = 25°C
- EXTREMELY HIGH CONTROL INPUT IMPEDANCE (control circuit isolated from signal circuit 10^{12}Ω typ.)
- LOW CROSSTALK BETWEEN SWITCHES : 50dB Typ. at f_{IS} = 0.9MHz, R_L = 1KΩ
- MATCHED CONTROL - INPUT TO SIGNAL OUTPUT CAPACITANCE : REDUCES OUTPUT SIGNAL TRANSIENTS
- FREQUENCY RESPONSE SWITCH ON : 40MHz (Typ.)
- QUIESCENT CURRENT SPECIF. UP TO 20V
- 5V, 10V AND 15V PARAMETRIC RATINGS



DIP

SOP

ORDER CODES

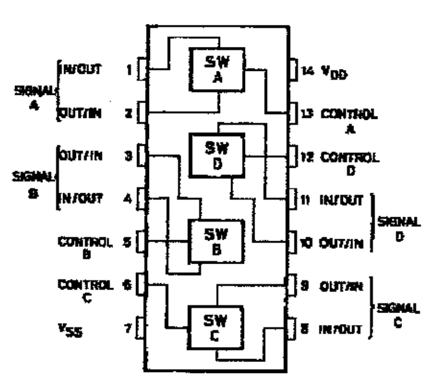
PACKAGE	TUBE	T & R
DIP	HCF4066BEY	
SOP	HCF4066BM1	HCF4066M013TR

- INPUT LEAKAGE CURRENT I_I = 100nA (MAX) AT V_{DD} = 18V T_A = 25°C
- 100% TESTED FOR QUIESCENT CURRENT
- MEETS ALL REQUIREMENTS OF JEDEC JESD13B " STANDARD SPECIFICATIONS FOR DESCRIPTION OF B SERIES CMOS DEVICES"

DESCRIPTION

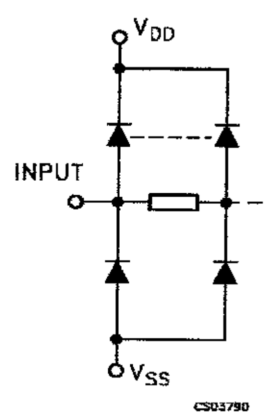
The HCF4066B is a monolithic integrated circuit fabricated in Metal Oxide Semiconductor technology available in DIP and SOP packages.
The HCF4066B is a QUAD BILATERAL SWITCH intended for the transmission or multiplexing of analog or digital signals.
It is pin for pin compatible with HCF4016B, but exhibits a much lower ON resistance. In addition,

PIN CONNECTION



the ON resistance is relatively constant over the full input signal range. The HCF4066B consists of four independent bilateral switches. A single control signal is required per switch. Both the p and n device in a given switch are biased ON or OFF simultaneously by the control signal. As shown in schematic diagram , the well of the n-channel device on each switch is either tied to the input when the switch is ON or to V_{SS} when the switch is OFF. This configuration eliminates the variation of the switch-transistor threshold voltage with input signal, and thus keeps the ON resistance low over the full operating signal range. The advantages over single channel switches include peak input signal voltage swings equal to the full supply voltage, and more constant ON impedance over the input signal range. For sample and hold applications, however, the HCF4016B is recommended.

INPUT EQUIVALENT CIRCUIT



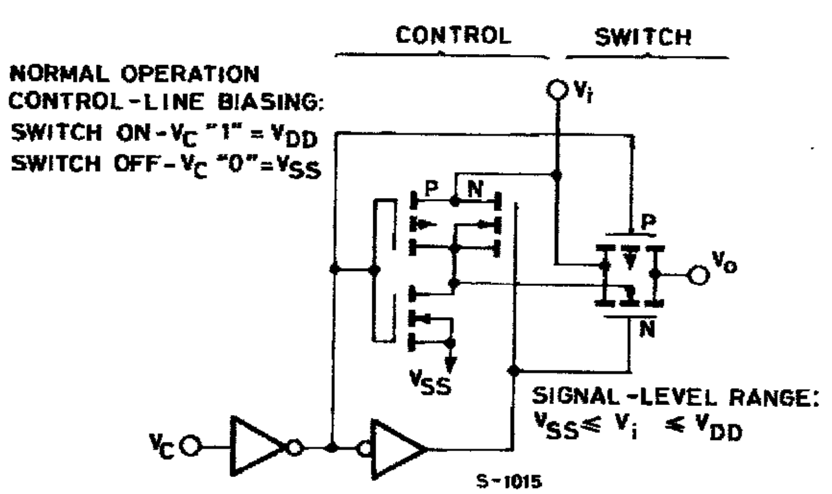
PIN DESCRIPTION

PIN No	SYMBOL	NAME AND FUNCTION
1, 4, 8, 11	A to D I/O	Independent Inputs/Outputs
2, 3, 9, 10	A to D O/I	Independent Outputs/Inputs
13, 5, 6, 12	CONTROL A to D	Enable Inputs
7	V_{SS}	Negative Supply Voltage
14	V_{DD}	Positive Supply Voltage

TRUTH TABLE

CONTROL	SWITCH FUNCTION
H	ON
L	OFF

SCHEMATIC DIAGRAM (1 OF 4 IDENTICAL SWITCHES AND ITS ASSOCIATED CONTROL CIRCUITY)



ABSOLUTE MAXIMUM RATINGS

Symbol	Parameter	Value	Unit
V_{DD}	Supply Voltage	-0.5 to +22	V
V_I	DC Input Voltage	-0.5 to V_{DD} + 0.5	V
I_I	DC Input Current	± 10	mA
P_D	Power Dissipation per Package	200	mW
	Power Dissipation per Output Transistor	100	mW
T_{op}	Operating Temperature	-55 to +125	°C
T_{stg}	Storage Temperature	-65 to +150	°C

Absolute Maximum Ratings are those values beyond which damage to the device may occur. Functional operation under these conditions is not implied.
All voltage values are referred to V_{SS} pin voltage.

RECOMMENDED OPERATING CONDITIONS

Symbol	Parameter	Value	Unit
V_{DD}	Supply Voltage	3 to 20	V
V_I	Input Voltage	0 to V_{DD}	V
T_{op}	Operating Temperature	-55 to 125	°C

ELECTRICAL CHARACTERISTICS

(T_{amb} = 25°C,Typical temperature coefficient for all V_{DD} value is 0.3 %/°C)

Symbol	Parameter	Test Condition			Value							Unit
			V_I (V)	V_{DD} (V)	T_A = 25°C			-40 to 85°C		-55 to 125°C		
					Min.	Typ.	Max.	Min.	Max.	Min.	Max.	
I_L	Quiescent Device Current (all switches ON or all switches OFF)		0/5	5		0.01	0.25		7.5		7.5	µA
			0/10	10		0.01	0.5		15		15	µA
			0/15	15		0.01	1		30		30	µA
			0/20	20		0.02	5		150		150	µA
SIGNAL INPUTS (V_{IS}) and OUTPUTS (V_{OS})												
R_{ON}	Resistance	V_C=V_{DD} R_L = 10KΩ Return to (V_{DD}-V_{SS})/2 V_{IS} = V_{SS} to V_{DD}		5		470	1050		1200		1200	Ω
				10		180	400		500		500	Ω
				15		125	240		300		300	Ω
Δ_{ON}	Resistance ΔR_{ON} (between any 2 of 4 switches)	R_L = 10KΩ, V_C = V_{DD}		5		5						Ω
				10		10						Ω
				15		15						Ω
TDH	Total Harmonic Distortion	V_C = V_{DD} = 5V, V_{SS} = -5V V_{IS} (p-p) = 5V, R_L = 10KΩ (sine wave centered in 0V) f_{IS} = 1KHz sine wave				0.4						%
	-3dB Cutoff Frequency (Switch on)	V_C = V_{DD} = 5V, V_{SS} = -5V V_{IS} (p-p) = 5V, R_L = 1KΩ (sine wave centered in 0V)				40						MHz
	-50dB Feedthrough Frequency (switch off)	V_C = V_{SS} = -5V V_{IS} (p-p) = 5V, R_L = 1KΩ (sine wave centered in 0V)				1						MHz

Symbol	Parameter	Test Condition			Value							Unit
			V_I (V)	V_{DD} (V)	$T_A = 25°C$			-40 to 85°C		-55 to 125°C		
					Min.	Typ.	Max.	Min.	Max.	Min.	Max.	
	-50dB Crosstalk Frequency	$V_{C(A)} = V_{DD} = +5V$ $V_{C(B)} = V_{SS} = -5V$ $V_{IS(A)} = 5V$ (p-p) 50Ω source, $R_L = 1K\Omega$				8						MHz
t_{pd}	Propagation Delay Time (signal input to output)	$R_L = 200K\Omega$, $V_C = V_{DD}$ V_{SS} = GND, $C_L = 50pF$ $V_{IS} = 10V$ square wave centered on 5V t_r, t_f = 20ns				20	40					ns
						10	20					ns
						7	15					ns
C_{IS}	Input Capacitance	$V_C = V_{SS} = -5$		+5		8						pF
C_{OS}	Output Capacitance	$V_C = V_{SS} = -5$		+5		8						pF
C_{IOS}	Feedthrough	$V_C = V_{SS} = -5$		+5		0.5						pF
	Input/Output Leakage Current Switch OFF	$V_C = 0V$ $V_{IS} = 18V$, $V_{OS} = 0V$ $V_{IS} = 0V$, $V_{OS} = 18V$		18		$\pm10^{-3}$	±0.1		±1		±1	µA
CONTROL (V_C)												
V_{ILC}	Control Input Low Voltage	$\|I_{IS}\| < 10\ \mu A$ $V_{IS} = V_{SS}$, $V_{OS} = V_{DD}$ and $V_{IS} = V_{DD}$, $V_{OS} = V_{SS}$		5			1		1		1	V
				10			2		2		2	V
				15			2		2		2	V
V_{IHC}	Control Input High Voltage			5	3.5			3.5		3.5		V
				10	7			7		7		V
				15	11			11		11		V
I_I	Input Leakage Current	$V_{IS} \leq V_{DD}$ $V_{DD} - V_{SS} = 18V$		18		$\pm10^{-5}$	±0.1		±1		±1	µA
	Crosstalk (control input to signal output)	$V_C = 10V$ (sq. wave) t_r, t_f = 20ns $R_L = 10K\Omega$		10		50						mV
	Turn - On Propagation Delay Time	$V_{IN} = V_{DD}$, t_r, t_f = 20ns $C_L = 50pF$, $R_L = 1K\Omega$		5		35	70					ns
				10		20	40					ns
				15		15	30					ns
	Control Input Repetition Rate	$V_{IS} = V_{DD}$, V_{SS} = GND $R_L = 1K\Omega$ to GND $C_L = 50pF$, $V_C = 10V$ sq. wave center on 5V t_r, t_f = 20ns $V_{OS} = 1/2 V_{OS}$ at 1KHz		5		6						MHz
				10		9						MHz
				15		9.5						MHz
C_I	Input Capacitance	Any Input				5	7.5					pF