ELECTROMAGNETIC LEVITATOR

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This report is submitted in partial fulfillment of the requirements for the award of Bachelor of Electronic Engineering (Industrial Electronics) With Honours

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To my beloved father, mother, and all my siblings and friends.

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ABSTRACT

This project is about the design of the control switch of magnetic controlled components. It deals with the knowledge of electromagnetism together with the control switching application. It is a method of supporting objects which is based on the physical property of the force between two magnetized bodies. This principle is used in electromagnetic levitator to levitate metallic object by generate a controlled magnetic force. Based on this principle, this project is designed by comprised of sensors, current control circuit and amplifier to regulate current. The sensors are used to detect the position of levitated object whether the object is closed to the electromagnet or far away from it. The top surface of the object should be in line with the sensors. The sensor will generate output signal to the PIC16F877A for processing in order to switch the current that pass through the electromagnet. The amplifier amplifies the PIC output signal to enhance the ability of the electromagnet to levitate heavier objects. This technique is the principle of the technology used by the maglev trains. These trains will float over a guide way and travel up to 300 miles per hour by using the basic principles of magnets to replace the old steel wheel and track trains.

ABSTRAK

Projek ini menggunakan konsep menarik dan melepaskan logam dari elektromagnet tanpa menggunakan magnet kekal. Komponen pengesan digunakan untuk mengesan kedudukan logam yang diletakkan, dan menghantar isyarat kepada sistem program dan akan diproses dengan mangikut program yang telah diprogramkan. Sekiranya pengesan mengesan logam berada di kedudukan berdekatan dengan elektromagnet, isyarat akan dihantar kembali kepada litar supaya elektromagnet menolak logam itu. Sekiranya logam berada di kedudukan jauh dari elektromagnet, isyarat akan dihantar kepada litar supaya elektromagnet dapat menarik kembali logam itu. Objektif utama projek ini adalah untuk menghasilkan sebuah projek yang sejajar dengan pembelajaran pengawalan suis. Di samping itu, projek ini juga bertujuan untuk mengkaji proses penghantaran data dari litar kepada sistem program. Untuk memastikan projek ini dihasilkan dengan berjaya, setiap jenis komponen harus dikaji supaya tidak berlaku kesilapan. Di samping itu, jenis program yang digunakan harus betul dan sesuai digunakan untuk projek ini. Kajian harus dibuat terlebih dahulu supaya dapat dibetulkan sekiranya terdapati kesilapan.

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LIST OF ABBREVIATIONS

AC	-	Alternative Current
ADC	-	Analog-to-Digital Converter
BJT	-	Bipolar Junction Transistor
DAC	-	Digital-to-Analog Converter
DC	-	Direct Current
EDS	-	Electrodynamics Suspension
EM	-	Electromagnetics
EMS	-	Electromagnetic Suspension
IC	-	Integrated Circuit
LED	-	Light Emitting Diode
LSB	-	Least Significant Bit
MSB	-	Most Significant Bit
NPN	-	Negative-Positive-Negative
PCB	-	Printed Circuit Board
PIC	-	Programmable Integrated Circuit
PNP	-	Positive- Negative- Positive

CHAPTER I

INTRODUCTION

This chapter contains the introduction of the project that comprises of the project background, objectives, problem statement, scope, methodology, and report structure of the project.

1.1 Project Background

This project is about the design of control switch of magnetic controlled component. It deals with the knowledge of electromagnetism together with the control switching application. It is a method of supporting objects which is based on the physical property at which the force between two magnetized bodies. In electromagnetic levitation, this basic principle is used to levitate metal by generate a controlled magnetic force. Using infrared sensors, current control circuit and amplifier, metallic objects can be floated just underneath the electromagnet. With the object floating underneath the electromagnet, an arrangement of infrared diode and infrared detector provides a signal to a feedback circuit to know the object's position. The circuit controls current to an electromagnet to maintain equilibrium between the force of the magnet and gravity. Thus, the object floats. Impart a bit of a spin to the object and momentum will carry it for quite a long time as the only friction working against it is between the object and the air.

1.2 Objectives

There are three objectives of this project. Firstly, to design an electromagnetic levitator that works deal with the knowledge of electromagnetism and control switching application. Secondly, to study the process of induction electromagnet that related to the electromagnetic levitation project. Thirdly, to design and simulate the switching circuit using PIC microcontroller.

1.3 Problem Statement

The technology used in this project is similar to maglev train that levitates metal without touching magnet. Thus the maglev train could travel at more than 300 miles per hour because of the friction working against it is only the air friction. The current control is used to switching system. It is very important in this project because of the levitator is designed to levitate a certain amount of weight of metallic objects. The current flows through the electromagnet and then will generate magnetic force to attract the metallic objects. By controlling the current flow as a result can attract and float a certain weight of the objects. The stability of system is a crucial factor to affect the levitation process. Therefore continuous study is done to implement the PIC controller into the levitator system to switch the current automatically according to the various weights of the objects.

1.4 Scope

The scope of this project is focused on levitating a small metal object in the midair. By using electromagnet, photo sensor and closed loop control, small and light metal objects can be floated just underneath the magnet. For non-metallic and heavier objects (out of the electromagnet's field strength), they are not to be considered. Since this is a low cost project, thus the magnetic field strength is limited to low field strength.

1.5 Methodology

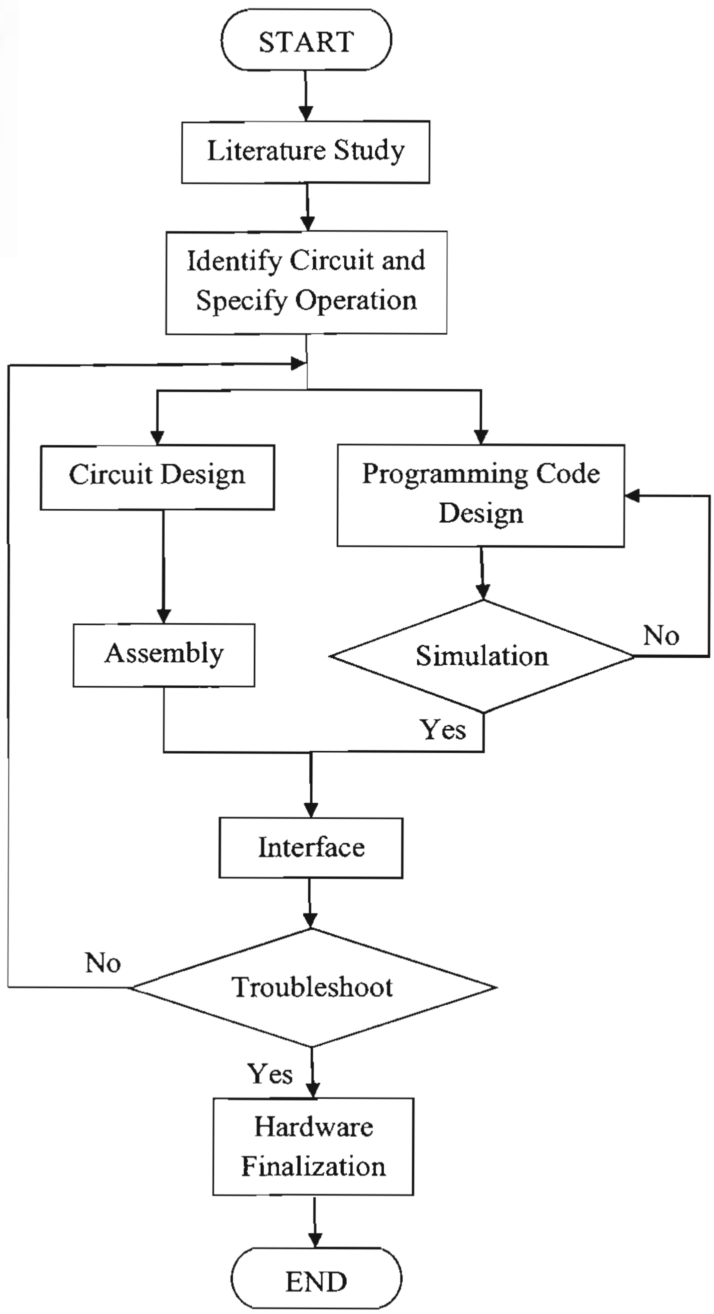


Figure 1.1 Flow chart of methodology.

This project starts from searching for literature reviews from resources like books, journals, and internet resources. From the resources, some circuits and information that are related to the project are studied and learnt.

Then the levitation circuit is identified from the resources. After having enough information, circuit is designed by using PROTEUS. Besides that, the programming code for PIC controller is designed by using CCS C Compiler.

After the circuit is designed, the next step is assembly the circuit by using PCB board. For the programming code, it is simulated and make sure there is no error within the coding. Then the completed circuit is interfaced with the model.

Eventually, troubleshooting process is executed to test and troubleshoot the circuit. If the circuits not function well, redesign and reconstruct circuits will be carried out to insure the circuit will function as expected.

1.6 Thesis Layout

This report comprises of 7 chapters. The Chapter I is the introduction of this project that includes the project background, objectives, scope, problem statement, and methodology of this project.

Chapter II is the literature review based on the electromagnetic levitation, electromagnetic coil, sensor, Op-amp, PIC16F877A, R-2R ladder DAC, and BJT transistor. This chapter explains the resources and articles that are related to the project, and also consists of the products available of the market nowadays.

Chapter III is about the circuit design. The circuit is connected to a coil to levitate a magnetic object. Each component used in circuit and circuit operation are explained in detailed here.

Software design is elaborated in Chapter IV. The program of PIC for control switching current is explained here.

The simulation, troubleshooting results, and the analysis of the project will be explained in Chapter V.

The Chapter VI is about the discussions of this project and mainly for the design process, problem statement and some new ideas.

The Chapter VII gives the overall conclusion and future recommendation regarding the project.

CHAPTER II

LITERATURE REVIEW

This chapter is about the discussions of the fundamental ideas of electromagnetic levitation system. The features of this project and all components used will be explained as well.

2.1 Introduction of Electromagnetic Levitation

Magnetic levitation systems have been widely studied and used in the past decades. Maglev high-speed trains and active magnetic bearings are examples of magnetic levitation application. "Magnetic levitation control system with single degree of freedom is a typical integration of mechanical and electrical systems. It is the platform to study magnetic levitation technology, and can be used as a research base for vertical magnetic bearing apparatuses," explained by Jie Ma [1]. In addition, they described magnetic levitation as a technique that uses mechanical force to suspend an object, for instance rotor, so that no mechanical contact between stator and rotor. This gives absolute advantages to magnetic levitation technology with no friction loss, no abrasion, and no necessity for lubrication, long endurance, controllable support force and adjustable stiffness. Therefore, the frictionless mechanical movement is a significant field of study to completely overcome the mechanical losses.

There are three basic schemes using various aspects of diamagnetism that allow the levitation. Firstly, superconductors are ideal diamagnetic and completely expel magnetic field at low temperatures. For instance, a sumo wrestler standing on a levitating magnets platform that floats above a high-temperature superconductor. The superconductor cooled by liquid air that hidden below the platform.

Secondly, an object does not need to be superconducting to levitate. Living things also can levitate themselves if placed in a strong magnetic field. Although the majority of ordinary materials such as wood or plastic seem to be non-magnetic, they also expel a very small portion like 0.00001 of an applied magnetic field.

Figure 2.1 Frog had been levitated in a very small portion (Wikipedia).

Lastly, low temperature such that air turns liquid and powerful magnets such that cooking pans are drawn from a distance of several meters, are not what one is likely to have at home to be able to watch the superconducting or diamagnetic levitation [2].

Figure 2.2 The real levitation at fingertips (physics.ucla.edu).

There are several method that magnet can levitate objects. Firstly is the repulsion between like poles of permanent magnets or electromagnets. There need to be a way to constrains the magnets so that they don't flips over and become attracted to each other. Secondly is the repulsion between a magnet and a metallic conductor induced by relative motion. The magnet needs to be restrained from moving in the same direction as the conductor. Thirdly is the repulsion between a metallic conductor and AC electromagnet. It is possible to shape the magnetic field to keep the conductor constrained in its motions. After this is the repulsion between a magnetic field and a diamagnetic substance. This is the case of the floating frog, and the floating magnet between two diamagnetic disks.

For the repulsion between a magnet and a superconductor, they are no constraints are needed. Beside these, the attraction between unlike poles of permanent magnets or electromagnets will work as long as there is a mechanical method to constrain the magnets so they don't touch. Besides this, the attraction between a permanent magnet or electromagnet and a piece of iron is also can levitate objects. Then, the attraction between the open core of an electromagnetic solenoid and a piece of iron or a magnet will also levitate an object. The iron or magnet will touch the inside surface of the solenoid. The next is the attraction between an electromagnet and a piece of iron or a magnet, with sensor and active control of the current to the electromagnet used to maintain some distance between them. Last but not least, the repulsion between and electromagnet and a magnet, with sensors and active control of the current to the electromagnet used to maintain some distance between them [3].

Electromagnetic suspension is magnetic levitation that achieved by using servo controlled electromagnets. The attraction from a fixed strength magnet decreases with increased distance, and increases at closer distances. Stable magnetic levitation can be achieved by measuring the position of the object being levitated, and using a feedback loops which continuously adjusts one or more electromagnets to correct the object's motion. This is a termed of Electromagnetic suspension. The electromagnet is above the object being levitated, the electromagnet is turned off whenever the object gets too close, and turned back on when it falls further away.

The electromagnetic levitation technology is also applied to transportation. The maglev (magnetic levitation) is a system of transportation that using magnetic levitation to suspend, guide and propel vehicles, predominantly trains. This method has the potential to be faster, quieter and smoother than wheeled mass transit systems. The power needed for levitation is usually not a particularly large percentage of the overall consumption; most of the power used is needed to overcome air drag, as with any other high speed train. The highest recorded speed of a Maglev train is 581 kilometers per hour (361 mph), achieved in Japan in 2003 [4]. The implementation of maglev principle can be divided into three types- electromagnetic suspension (EMS), electrodynamics suspension (EDS), and inductrack system (permanent magnet EDS).

Electromagnetic Suspension (EMS) is the magnetic levitation of an object achieved by constantly altering the strength of a magnetic field produced by electromagnets. Magnetic levitation technology is important because it reduces energy consumption. It also increases energy efficiency by minimizing the contact points between frictional surfaces. The application of magnetic levitation is most commonly known for its role in Maglev trains.

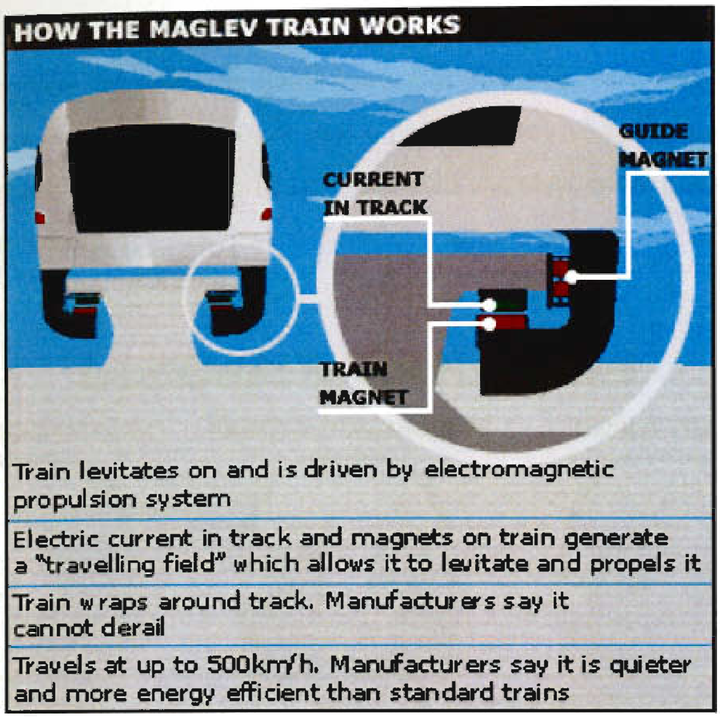


Figure 2.3 The working of a maglev train (BBC News 2008).

Electrodynamics suspension system is based on the repelling force of magnets. This type of trains uses super-cooled, superconducting electromagnets and it can conduct electricity even after the power supply has been shut off. Thus it can save energy but the cryogenic system uses to cool the coils can be expensive.

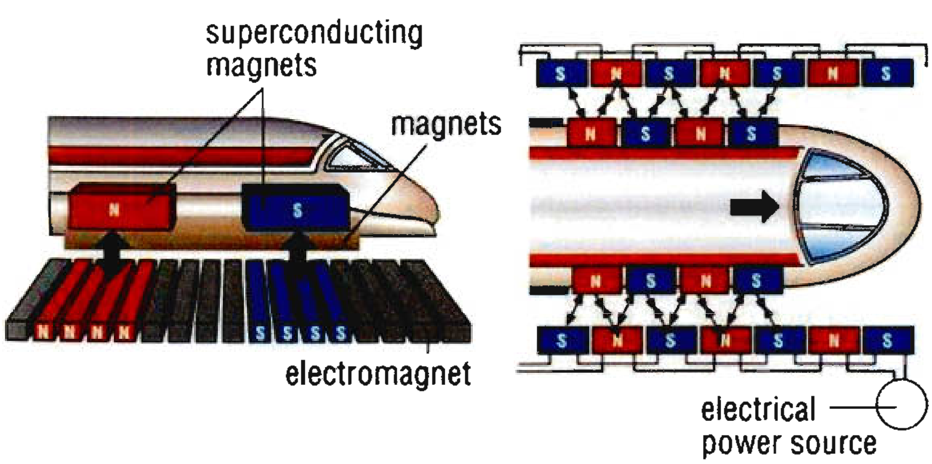


Figure 2.4 Maglev train using electrodynamics levitation (Mathiesen 2008).

The Inductrack is a newer type of EDS that uses permanent room-temperature magnets to produce the magnetic fields instead of powered electromagnets or cooled superconducting magnets. Inductrack uses a power source to accelerate the train only until begins to levitate. If the power fails, the train can slow down gradually and stop on its auxiliary wheels [5].

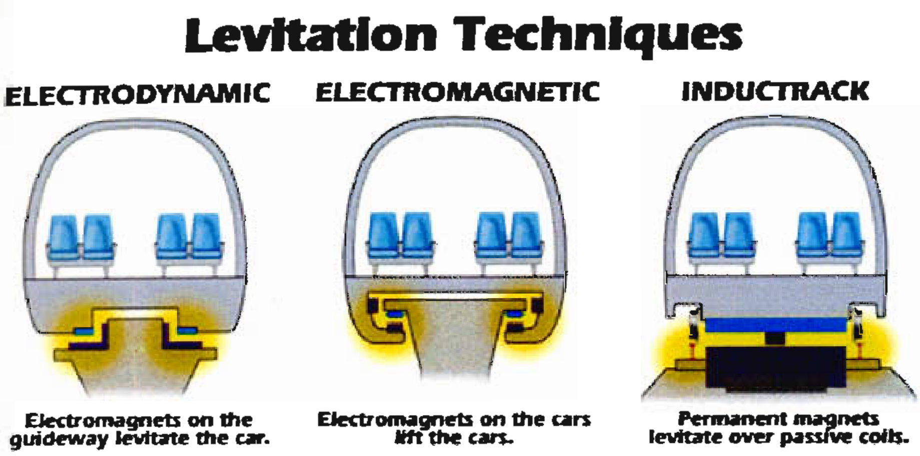


Figure 2.5 The three levitation techniques (Landovskis *et al.*).

2.2 Electromagnetic Coil

The electromagnetic levitation can be performed by using either attractive or repulsive force. In attractive levitation, a ferromagnetic body is attracted to a source of magnetic flux as a piece of steel is attracted to a permanent magnet. The attractive force can be created by dc current in a solenoid coil or permanent magnet. When a dc current is flows through a coil as shown in figure below, the coil will produce magnetic field. The magnetic field will be enlarged if an iron core is inserted in the solenoid. The north pole is acts as repulsion pole while the south pole represents the attraction pole [6]. The characteristics of solenoid now is likes a permanent magnet.

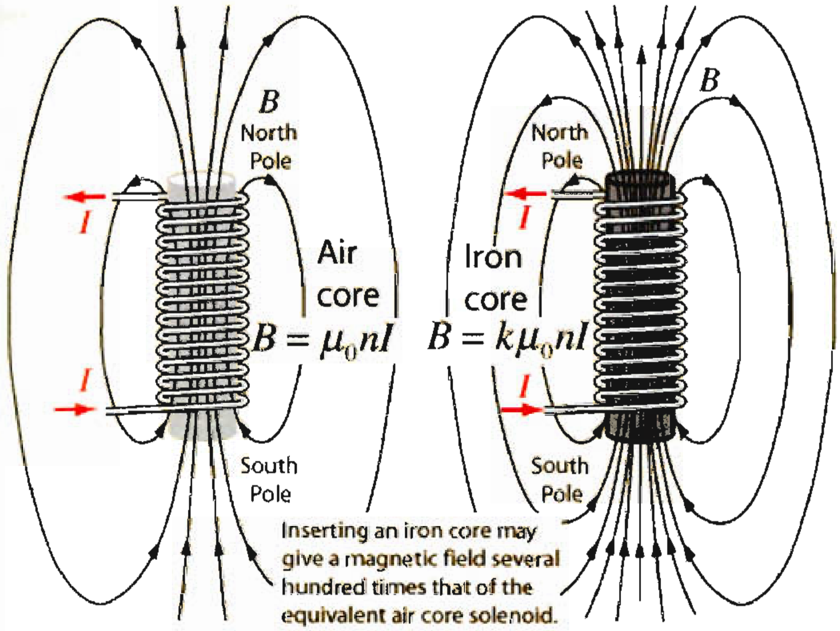


Figure 2.6 The magnetic field between air core and iron core (HyperPhysics).

The current flows through a coil will generate magnetic field. The strength of magnetic field is depends on the amount of current flows and the number of turns of solenoid. The current flows and number of turns are directly proportional to the strength of magnetic field. The poles of solenoid can be determined by the current flows direction as shown in Figure 2.7.

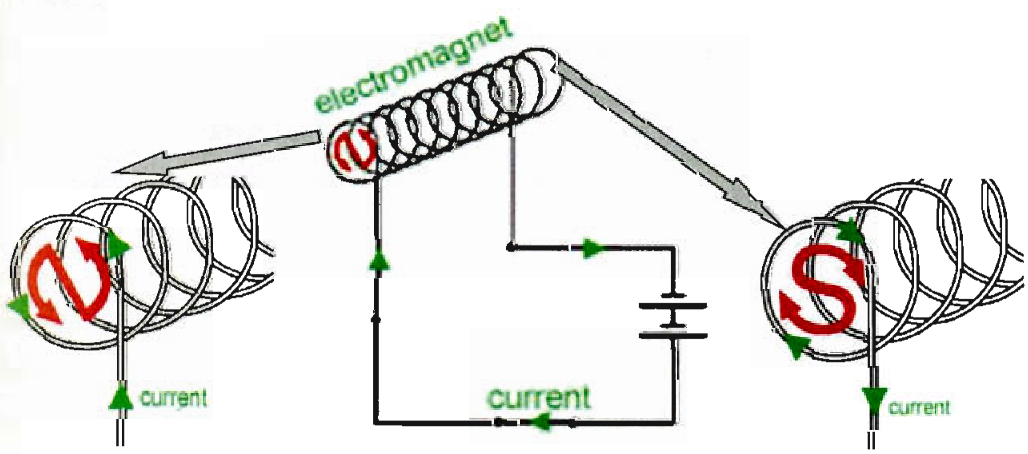


Figure 2.7 The north and south position when the current flows through the coil (resources.schoolscience.co.uk).

2.3 Sensor

In this project, infrared sensor is used to detect the position of levitated object. An infrared sensor is a LED made from gallium arsenide, which is emits near infrared energy at about 880*nm*. The infrared emits infrared that less noise and ambient light than at normal optical wavelengths. Since the infrared emitter based LED, so it has significant characteristics of LED.

LED is silicon device that produces light. The light is produced only when current passes through in the forward direction. To produce light, the forward voltage V_f must be higher than the diode's internal barrier voltage as shown in figure below. The LED only passes current in forward direction and block current in reverse direction.

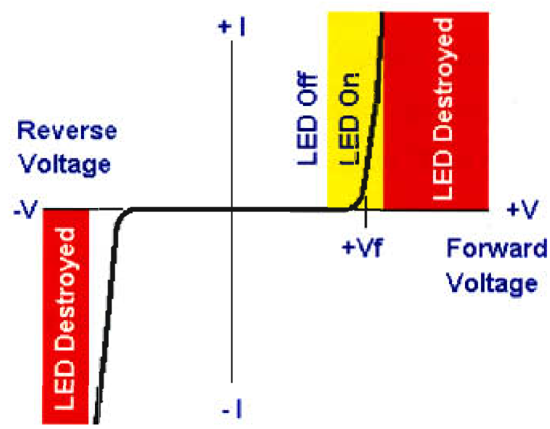


Figure 2.8 The region of LED turns on (Hansen 2008).

To protect the LED, a resistor is added as shown in figure below. The resistor is acts to limit the current flow pass through the LED, thus protects the LED from being destroyed. The LED has a cut-in voltage or diode forward voltage drop (V_d) that must be considered during the calculation of current flow. The current is calculated by [7].

$$I = (V_s - V_d)/220 \qquad (2.1)$$

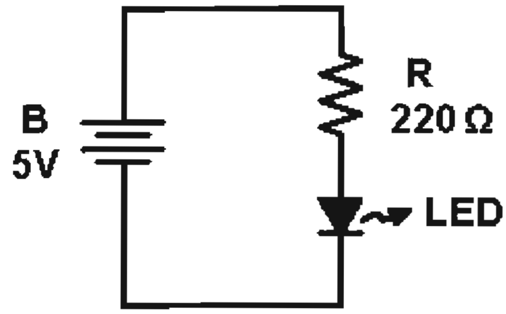


Figure 2.9 A current limiting resistor limits the current pass through LED (Hansen 2008).

By using the infrared emitter to sense the position of levitated object, a photodetector is used to detect the emitted infrared. Photodetector consists of photodiode and phototransistor type. A photodiode is a type of photodetector capable of converting light into either current or voltage. It is a PN junction structure and it operates to the fact of photons impinging on the PN junction also alter the reverse current-versus-voltage characteristics of the diode. In particular, the reverse current will be increased almost linearly with light intensity. Thus the photodiode is operated in the reversed-bias mode.

Phototransistors also consist of a photodiode with internal gain. In this sensor, the intensity of EM radiation impinging on the collector-base junction of the transistor acts much like a base current in producing an amplified collector-emitter current. The response of phototransistor is not as fast as photodiode, but still responses in microseconds. It is limited with maximum response in the infrared but usable range in the visible band. The light detection circuit of phototransistor can be constructed as Figure 2.10. The output voltage obtained by the voltage divider of phototransistor and it is connected to a voltage follower [8].

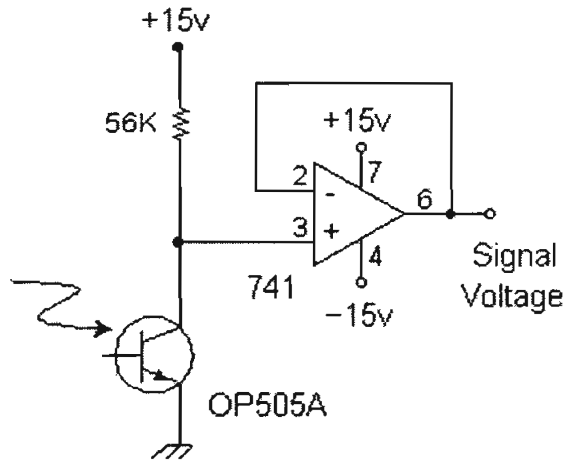


Figure 2.10 Construction of phototransistor detection circuit (Hansen 2008).

2.4 Operational Amplifier

Operational amplifier (op-amp) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, a single-ended output. Op-amp produces an output voltage up to hundreds of thousands times larger than the voltage difference between its input terminals.

The op-amp is one type of differential amplifier. Other types of differential amplifier include the fully differential amplifier (two outputs differential amplifier), instrumentation amplifier (built from three op-amps), isolation amplifier (similar to the instrumentation amplifier, but with tolerance to common-mode voltages that would destroy an ordinary op-amp), and negative feedback amplifier (usually built from one or more op-amps and a resistive feedback network).

The amplifier's differential inputs consist of a V+ input and a V- input, where the V+ is non-inverting input while the V- is inverting input.

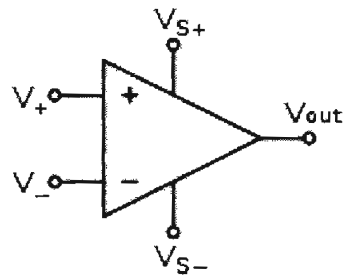


Figure 2.11 Circuit diagram symbol for an op-amp (Wikipedia).

The op-amp has an open-loop gain of up to 10000. So a closed-loop or negative feedback design is applied on the op-amp to reduce the gain and also to predict the output voltage. Figure below is a negative feedback op-amp with feedback resistor and ground resistor. The V_{out} is equals to Equation 2.2. This type of op-amp configuration is called non-inverting amplifier.

$$V_{in}(R_f / R_g + 1) \qquad (2.2)$$

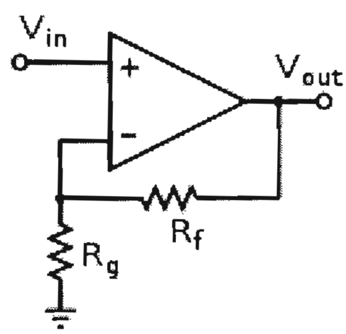


Figure 2.12 Non-inverting amplifier (Wikipedia).

For inverting amplifier, the input voltage is applied at negative input of op-amp through a resistor and then a negative feedback as shown in Figure 2.13. The loop gain is $-R_f / R_{in}$. Thus the output voltage is negative $-V_{out}$.

A resistor is often inserted between the non-inverting input and ground reducing the input offset voltage due to different voltage drops due to bias current, and may reduce distortion in some op-amps.

A dc-blocking capacitor may be inserted in series with the input resistor when a frequency response down to DC is not needed and any DC voltage on the input is unwanted. That is, the capacitive component of the input impedance inserts a DC zero and a low-frequency pole that gives the circuit a bandpass or high-pass characteristic.

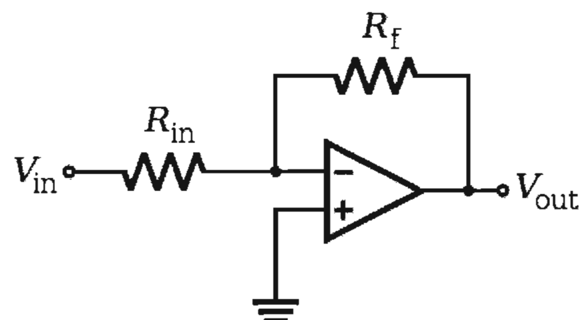


Figure 2.13 Inverting amplifier (Wikipedia).

A unity gain buffer amplifier or voltage follower is configured by applying a negative feedback to an op-amp and connecting the signal source to the non-inverting input. This configuration has very high input impedance (1 $M\Omega$ to 10 $T\Omega$), meaning that the input does not load down the source or draw any current from it. Because the output impedance of the op-amp is very low, it drives the load as if it were a perfect voltage source. The voltage follower reduces power consumption in the source, distortion from overloading, crosstalk and other electromagnetic interference [9].

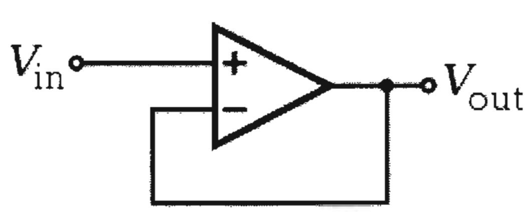


Figure 2.14 An op-amp based unity gain buffer amplifier (Wikipedia).

2.5 PIC16F877A

PIC microcontrollers are based on RISC (Reduced Instruction Set Computer) architecture and therefore normally they use 35 instructions. The PICs can be erasable and programmable Flash memory for program storage. In this project, a PIC16F877A is chosen to control switching current. PIC16F877A is an easy-to-program CMOS Flash based 8-bits microcontroller and it uses only 35 single word instructions. It has 40-pins that each of pin has its own function. The microcontroller consists of two comparators, 8-channels of 10-bit Analog-to-Digital (A/D) converter, 2 PWM functions and 5 I/O ports.

The PIC16F877A is one of the PIC in the family of PIC16F87XA. Hence there are more PICs that are similar to it. The other types of PIC and their features are shown in the table below.

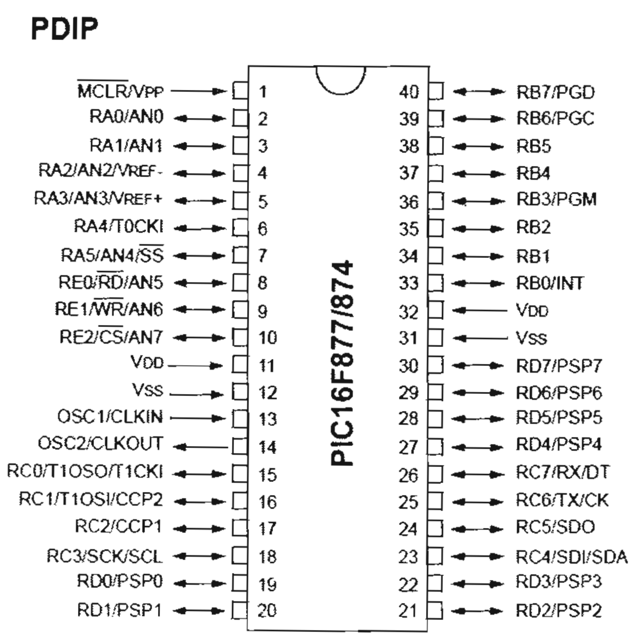


Figure 2.15 PIC16F877A (Microchip).

Table 2.1 The features of PIC16F87XA (Microchip).

	PIC16F873A	PIC16F874A	PIC16F876A	PIC16F877A
Flash Program Memory (14-bits words)	4K	4K	8K	8K
Data Memory (Bytes)	192	192	368	368
EEPROM Data Memory (Bytes)	128	128	256	256
Interrupts	14	15	14	15
I/O Ports	Ports A, B, C	Ports A, B, C, D, E	Ports A, B, C	Ports A, B, C, D, E
Serial Communications	MSSP, USART	MSSP, USART	MSSP, USART	MSSP, USART
Parallel Slave Port	No	Yes	No	Yes
10-bits Analog-to-Digital Module	5 input channels	8 input channels	5 input channels	8 input channels
Packages	28-pins PDIP 28-pins SOIC 28-pins SSOP 28-pins QFN	40-pins PDIP 44-pins PLCC 44-pins TQFP 44-pins QFN	28-pins PDIP 28-pins SOIC 28-pins SSOP 28-pins QFN	40-pins PDIP 44-pins PLCC 44-pins TQFP 44-pins QFN

2.6 R-2R Ladder DAC

Resistor ladder networks provide a simple, inexpensive way to perform digital to analog conversion (DAC) [10]. The most popular networks are the binary weighted ladder and the R-2R ladder. Both devices will convert digital voltage information to analog, but the R-2R ladder has become the most popular due to the network's inherent accuracy superiority and ease of manufacture. A basic R-2R resistor ladder network is shown in Figure 2.16. Bit D7 MSB (most significant bit) to Bit D0 LSB (least significant bit) is driven from digital logic gates. Ideally, the bits are switched between 0 volt (digital *0*) and V_{ref} (digital *1*). The R-2R network causes the digital bits to be weighted in voltage V_{out}. The circuit shows 8 bits and giving 2^8 of 256 possible outputs. The output voltage is depending on which bits are set to *1* and which to 0 [11].

For a digital value *VAL* and a R-2R DAC of *N* bits of 0 *V*/ V_{ref}, the output voltage V_{out} is:

$$V_{out} = V_{ref}\,[b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N}] \qquad (2.3)$$

Or in an easier way:

$$V_{out} = V_{ref} \text{ x } VAL \,/\, 2^N \qquad (2.4)$$

From the Figure 2.16, the $N = 8$ bits and hence $2^N = 256$. With $V_{ref} = 5V$, the output voltage

$V_{out} = 5$ x $1/ 255 = 0.0196V$, for minimum (single step) $VAL = 1$ (2.5)

$V_{out} = 5$ x $255/ 256 = 4.98V$, for maximum output (11111111 VAL = 255) (2.6)

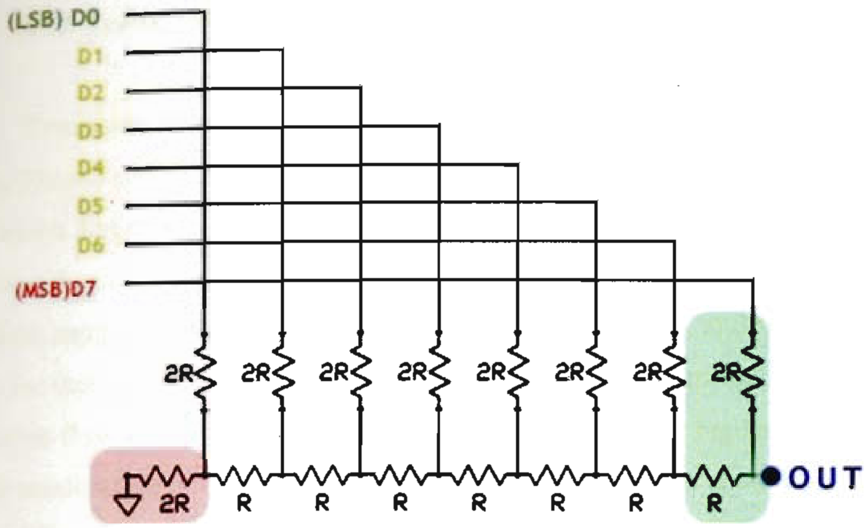


Figure 2.16 R-2R resistor network (International Resistive Company).

An Op-amp is connected to the output as shown as Figure 2.17. The Op-amp is added and it is to be considered as a buffer stage to provide a correct and desired output and eliminates the problem of adding resistor at the output.

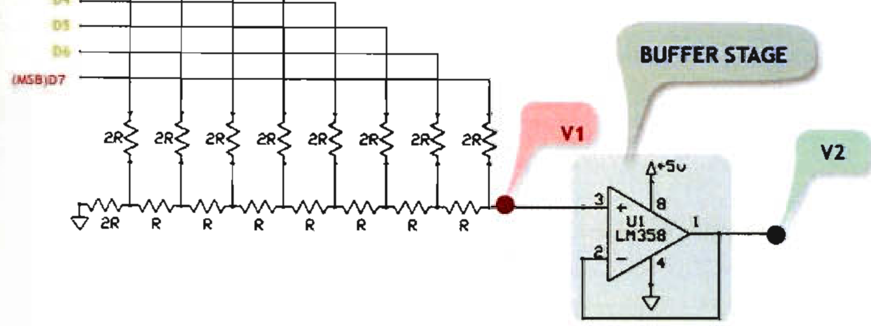


Figure 2.17 The digital analog converter and voltage buffer circuit (International Resistive Company).

2.7 BJT Transistor

Transistor is a semiconductor device used to amplify and switch electronic signal. This is accomplished by using a small amount of electricity to control a gate on a much larger supply of electricity. Transistors are composed of three parts- a base, a collector, and an emitter. The base is the gate controller device for the larger electrical supply. The collector is the larger electrical supply, and the emitter is the outlet for that supply. By sending varying levels of current from the base, the amount of current flowing through the gate from the collector may be regulated. In this way, a very small amount of current may be used to control a large amount of current, as an amplifier.

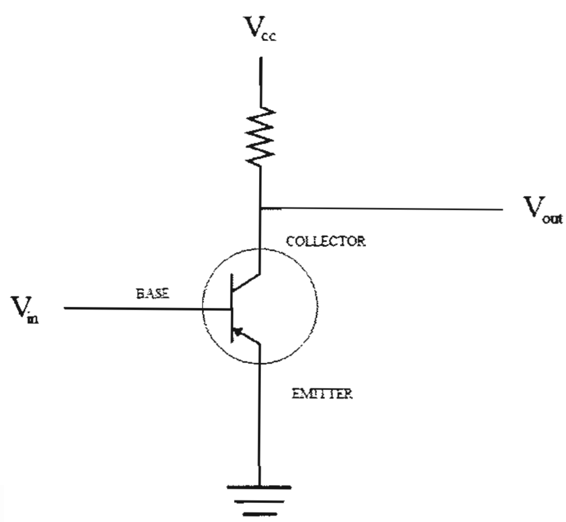


Figure 2.18 Simple circuit of a BJT transistor (Wikipedia).

The transistor is also can be as a switch. The condition of being as a switch is that the transistor is operating in operating region or out-of-operating region as shown in Figure 2.19. The cut-off region as shown in the figure, is that the transistor is switched fully off as the transistor are zero input base current (I_B), zero output collector current (I_C) and maximum collector voltage (V_{ce}) which results in a large depletion layer and no current flows through the device. The saturation region is represents the transistor will be biased so that the maximum amount of base current is applied, resulting in maximum collector current flow and minimum collector emitter voltage which results in the depletion layer being very small and maximum current flows through the device. Hence transistor is switched fully on [12].

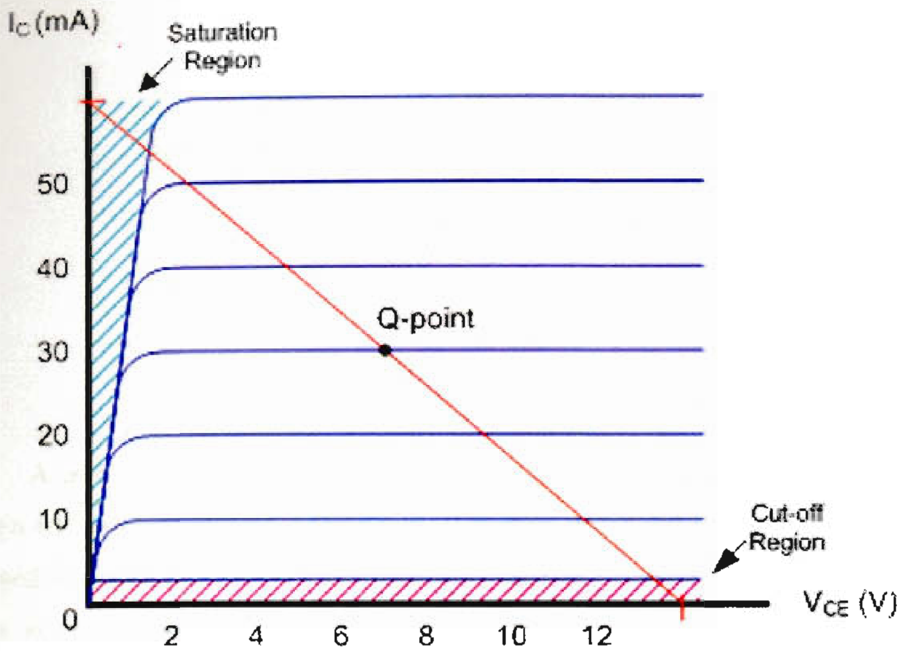


Figure 2.19 The region of operation for a transistor (Electronics- Tutorials).

For an NPN transistor, the layers of an NPN transistor must have the proper voltage connected across them which the voltage of the base must be more positive than that of the emitter. The voltages are supplied by a battery or some other source of direct current. The current passes from the emitter to the collector through the base. For PNP junction transistor, the emitter and collector are both a p-type semiconductor material and the base is n-type. A PNP junction transistor works on the same principle as an NPN transistor but it differs in one respect. The main flow of current in a PNP transistor is controlled by altering the number of holes rather than the number of electrons in the base. PNP transistor works properly only if the negative and positive connections to it are the reverse of those of the NPN transistor [13].

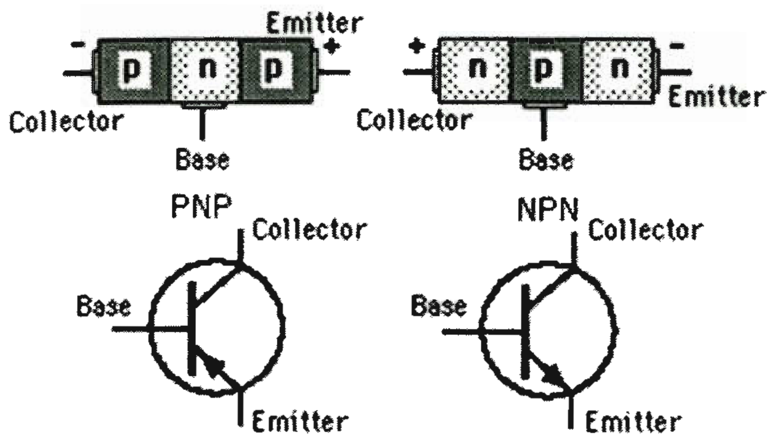


Figure 2.20 PNP and NPN transistor (GSU).

A transistor design is related to this project as shown in Figure 2.21. When using a transistor to turn on a relay coil, it is very important to use a 1N4001 diode reversed biased in parallel with the relay coil. This is to prevent the kickback voltage in the reverse polarity from destroying the transistor. This reverse voltage occurs momentarily when the normal current stops flowing through the coil.

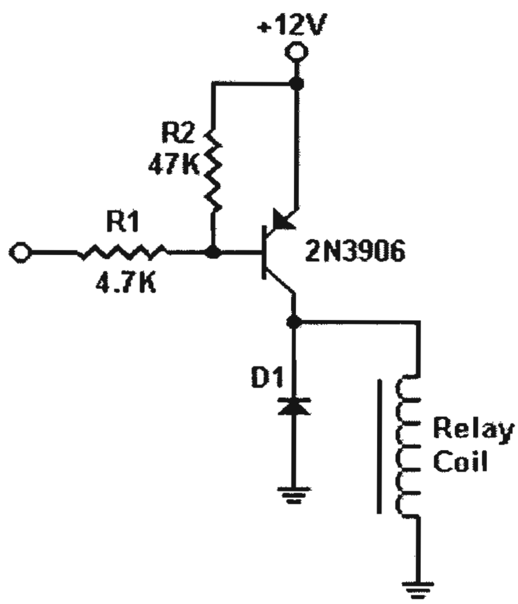


Figure 2.21 A diode is parallel to the coil to prevent the kickback voltage (Martell 2009).

CHAPTER III

CIRCUIT DESIGN

This chapter contains the process of design Electromagnetic Levitator. The levitator's operating process will be anatomized by the block diagram and the circuit.

3.1 Block Diagram

The Figure 3.1 shows the block diagram of the levitation system. The position sensors are infrared diode and infrared detector. Both of the diode and detector are types of LED, thus they have significant characteristics of LED. When the diode is on, it emits infrared radiation to the detector. The characteristic of output voltage of detector is refers to the Figure 3.2. The detector will output a voltage of V_{OC} regarding to the intensity of the infrared light. The V_{OC} represents the position of the object. If the object is fully blocks the radiation, the V_{OC} will be relatively very low. In contrast, when there is nothing blocks the radiation, the V_{OC} becomes maximum output voltage as the detector receives full radiation from the diode [14]. In order to float the object, it must be partially blocks the infrared radiation and the detector will give a range of output voltage, which is the position set point.

The output voltage of V_{OC} is fed into the current control circuit. The circuit consists of PIC, compensation circuit and amplifier to regulate the current flow through the electromagnet.

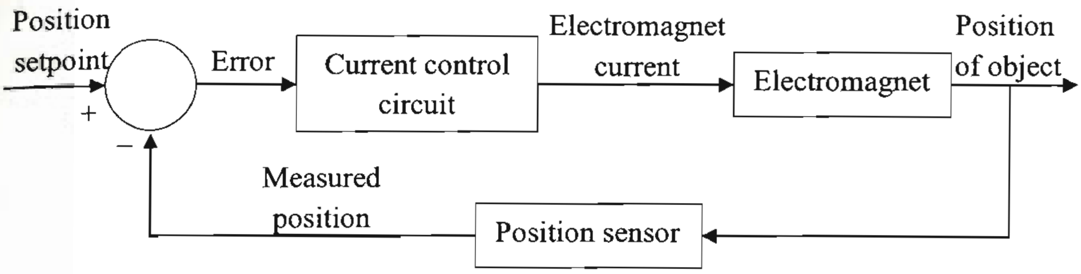


Figure 3.1 Block diagram of levitator system.

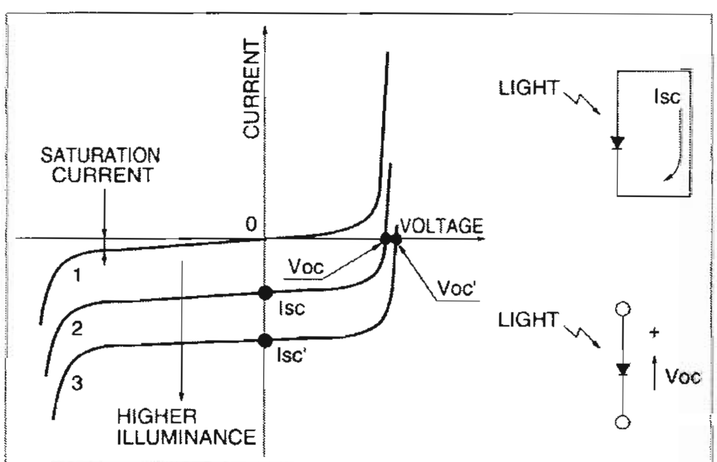


Figure 3.2 Voltage- current characteristics (Technical Information SD-12).

3.2 Electromagnetic Levitator Circuit

By referring to the block diagram, a circuit is designed as in Figure 3.3. There are three voltage regulators to regulate the $15V$ input to output voltage of $5V$, $9V$ and $12V$. The combination of diode 1N4001 and torch light are representing the infrared detector. From the circuit, the output of infrared detector is fed to PIC. The function of PIC is to switch the transistor Q1. When there is an object between the sensors and blocking the infrared radiation, the PIC switches on the transistor to keep the electromagnet coil powered on. Whenever the sensors cannot sense any object, or the object is completely blocking the infrared radiation, the PIC will switch off the transistor and immediately powered off the coil to prevent the coil overheating. The PIC output signal is in digital signal. R-2R ladder DAC is used to convert the digital signal to analog signal and then fed to the op-amp.

The op-amp is configured for a gain of two, [(R29/R21)/R21] buffers and amplifies the analog voltage. The output signal of the op-amp is fed to a second amplifier stage through the R22 and C8. The capacitor C8 forms a differentiator with the op-amp U3:B. The capacitor blocks slow voltage changes, but passes any rapid changes in the input signal and allows them to be amplified by the U3:B. The resistor of R22 and R18, R30 act to attenuate the slow voltage changes before they are amplified by the op-amp. The purpose of this compensation circuit is to perform closed-loop control using a combination of proportional and derivative modes to ensure the levitation is stable. Without it, the object would just flutter close to the electromagnet due to the system is unstable [15].

The filtered voltage is fed to second amplifier stage. The output signal drives transistor Q1 which has a dc current gain of more than 100 to vary the collector current. Because of the transistor is switching frequently, the transistor will get very hot during operation, thus a heat sink is attached on the transistor. The function of signal diode D6 is to prevent reverse biasing the base. When the transistor suddenly switches off, the two diodes 1N4001 provide a path for the excess current from the electromagnet coil so that it does not damage the transistor.

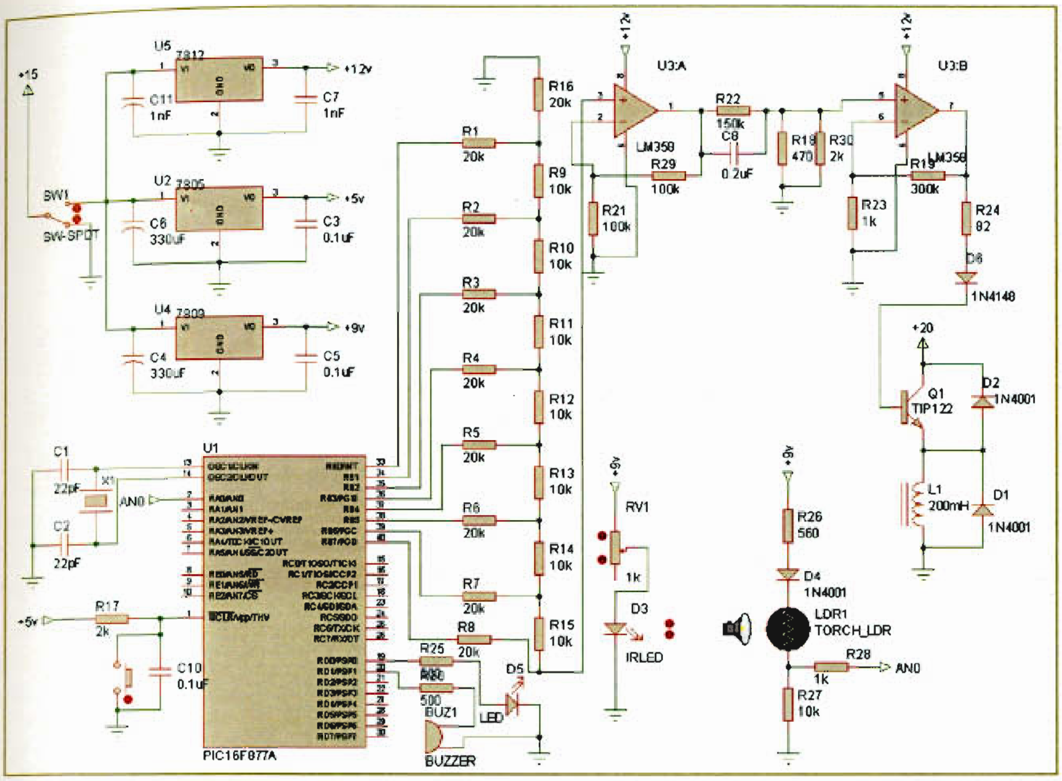


Figure 3.3 The circuit of electromagnetic levitator.

3.3 Printed Circuit Board

The integration of various parts needs a proper design of Printed Circuit Board (PCB) to ensure the functionality and operational of the system. Therefore, attention has to be given in PCB designing process. The schematic and PCB for the circuit is drawn by using Proteus 7.1 software. The steps below show the basic of producing good PCB layout.

i. Identify type of components will be used and type of packages.

ii. Identify type fixture, need of screw holes, heat sink mountings, and etc.

iii. Identify type jack, connector and terminal blocks which may be used.

iv. Set proper gap distance between connector and tracks.

v. Time and effort need to be spent for single layer board to avoid overlap traces.

vi. The size of power and ground traces has to be controlled.

vii. Data sheet are used to check proper pin out and to create new components.

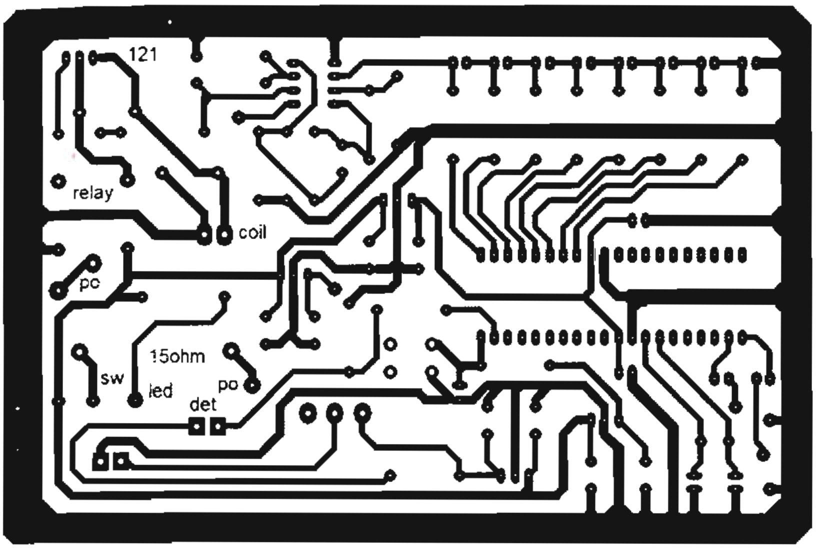


Figure 3.4 The PCB artwork.

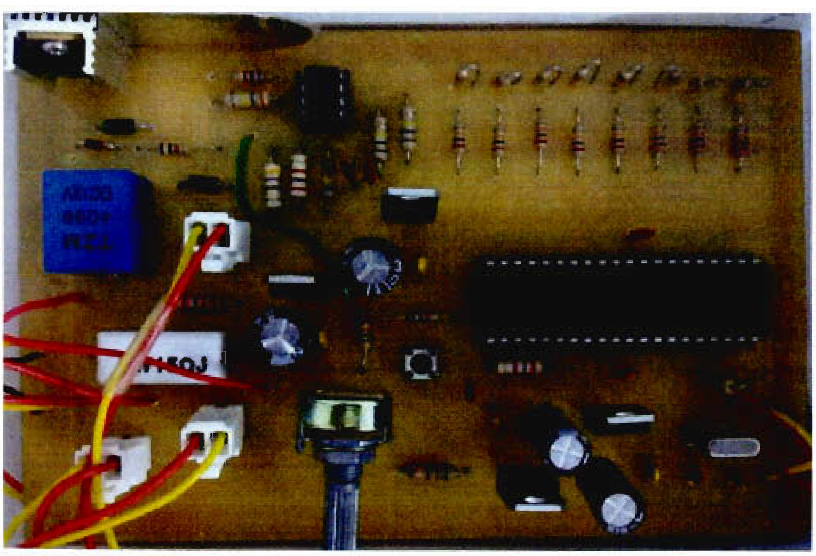


Figure 3.5 The circuit in PCB board.

CHAPTER IV

SOFTWARE DESIGN

This chapter contains the process of generating a C programming code for PIC microcontroller. The process is represented in flow chart.

4.1 Flow Chart

The programming code is written in CCS C Compiler. The coding is compiled and simulated with the circuit. Then the coding will be converted to HEX file in order to burn into PIC16F877A. After that, circuit assembly and interfacing with the PIC will be tested and troubleshoot.

The Figure 4.1 below shows the flow chart of the program. The program started at the sensor senses the position of levitated object and produces the analog signal (*input*) to the PIC. The PIC reads the *input* and then defines whether the *input* is in the range of between $0.7V$ and $4.5V$ or not. Then the pin RD0 and RD1 are act as indicator.

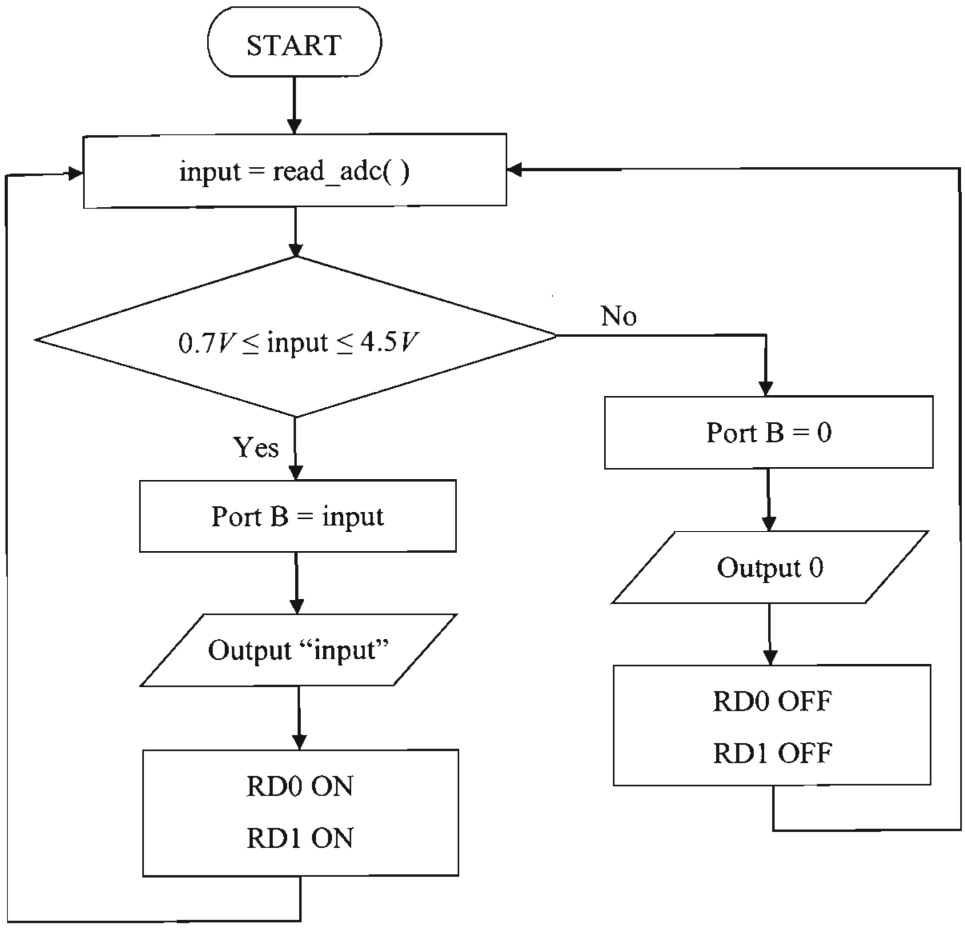


Figure 4.1 The flow chart of the PIC program.

4.2 PIC16F877A Coding

Before the program started, the *input* is declared as the analog input of the PIC. The command of analog-to-digital converter (ADC) conversion is declared and the pin *RA0* is used as ADC port. The while loop will always looping while the condition is true. Thus in this loop, the condition is true so the loop will be looping forever. The function of "if" loop is turn on or turn off the transistor when the input voltage is in the range of $0.7V$ to $4.5V$ or not. The range is converted to binary value of 100011_2 and 11100101_2 by the ADC. The pin RD0 and RD1 are connected to LEDs and buzzer respectively to act as indicator.

Program of PIC16F877A:

```
#include <16f877a.h>
#device adc=8
#fuses HS,NOWDT,NOPROTECT,NOLVP
#use delay (clock=20000000)
#byte PORTA=5
#byte PORTB=6
#byte PORTD=8
#use fast_io(A)
#use fast_io(B)

void main()
{
  unsigned int input;

  setup_adc( ADC_CLOCK_INTERNAL );
  setup_adc_ports(RA0_ANALOG);
  set_adc_channel( 0 );

  set_tris_b(0x00);
  set_tris_d(0xFD);
```

```
  while (TRUE)
  {
    input = read_adc();  //read analog input

  if (0b00100011 <= input && input <= 0b11100101)  //set operating range
  {
    output_b(input);
    output_high(pin_d0);
    output_high(pin_d1);
  }

  else
  {
    portb = 0x00;
    output_low(pin_d0);
    output_low(pin_d1);
  }
  }
}
```

CHAPTER V

RESULT AND ANALYSIS

This chapter is about the result and analysis of this project. The comparison between the expected and experimental results will be discussed and analyzed. Besides that, the components used in the circuit also will be discussed as well.

5.1 Sensors

The material used in infrared diode is AlGaAs, the radiant intensity is minimum $20mW/sr$ and maximum forward current is $100mA$. In the circuit of Figure 3.3, the potentiometer limits the forward current to the infrared LED to $15mA$. Since the diode is on all the time, thus the limiting current is purposed to protect the diode from burning.

From the experiment, the maximum output voltage of the infrared detector is $4.8V$. Thus the operating range of voltage to turn on the transistor Q1 is set at between $0.7V$ and $4.5V$. The minimum $0.7V$ is recommended as the minimum voltage to turn on the transistor is $0.6V$. There is a gap of $0.3V$ between the $4.5V$ and $4.8V$ to turn off the transistor when the object is reached at minimum position.

The output signal of the infrared detector is analyzed by using an oscilloscope. The probe is set to 10x and also the channel 1 coupling to AC mode. When the circuit is on and there is nothing presents between the infrared sensors, the output signal is as the Figure 5.1. The signal is flat due to the output signal is maintained. But when there is an object is levitating, the infrared radiation is being partially blocking, this will affect the output voltage of the detector. The Figure 5.2 is the output signal during levitation process. The oscillating signal is proportional to the position of the object [16].

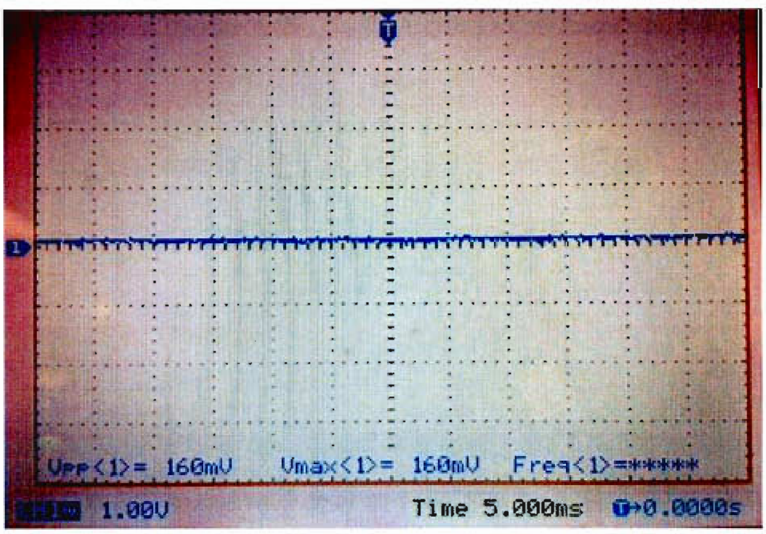


Figure 5.1 The output signal of the infrared detector when there is nothing blocking the infrared radiation.

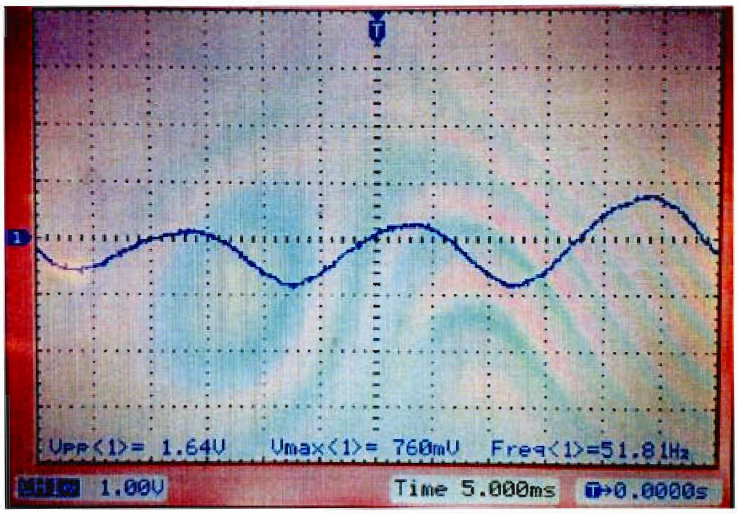


Figure 5.2 The output signal of the infrared detector when an object is blocking the infrared radiation.

5.2 Compensation Network

The compensation network is acts as a high pass filter to stabilize the control loop. The Figure 5.3 and Figure 5.4 show the signal before and after filtered and attenuated by the network. The Figure 5.4 shows a distinct smoother signal compare to the Figure 5.3. The unstable signal has been filtered and the noise is attenuated.

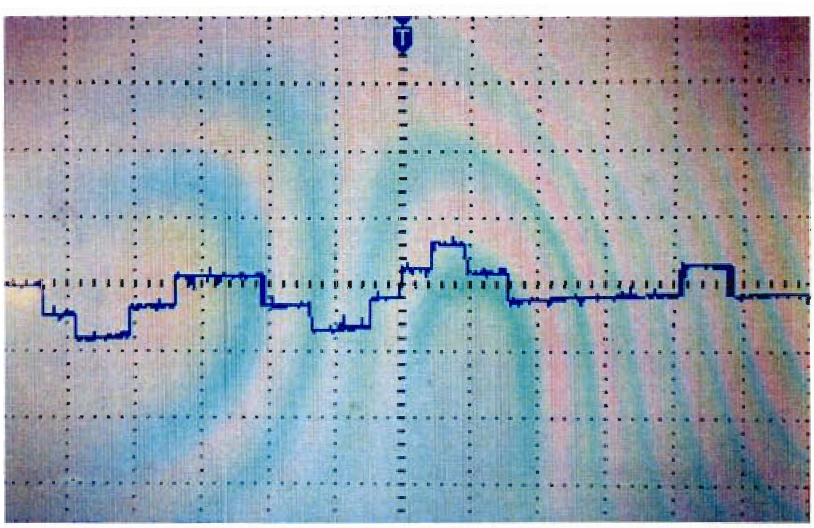


Figure 5.3 The signal before filtered and attenuated.

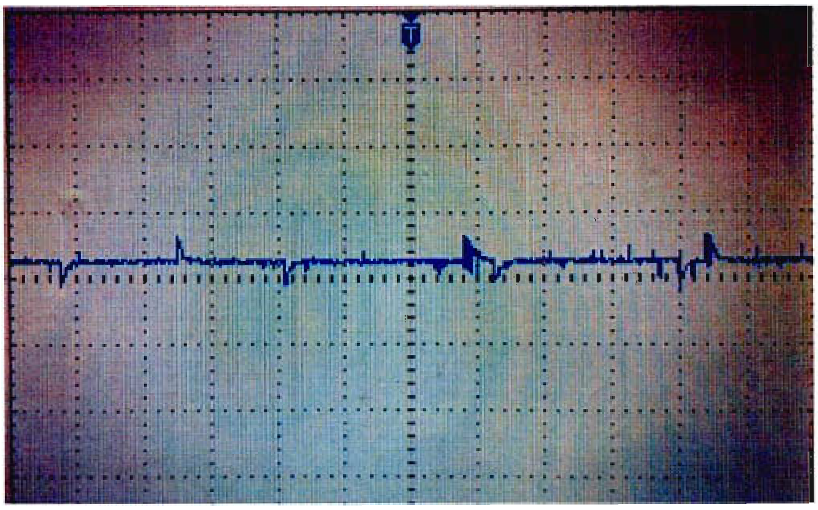


Figure 5.4 The signal after filtered and attenuated.

The compensation network is a crucial part of the system whereas the system stability is depends on the network. Thus many experiments are implemented to obtain the best suitable RC values to achieve the system stability. In the circuit of Figure 3.3, the capacitance value of C8 is $0.2\mu F$ and the resistance of the parallel R18 and R30 is 380.57Ω. Thus the cutoff frequency is:

$$f_{OL} = \frac{1}{2\pi RC}$$
$$= \frac{1}{2\pi \times 380.57 \times 0.2 \times 10^{-6}} \quad (5.1)$$
$$= 2.091kHz$$

The Equation 5.1 is used to calculate the cutoff frequency of the output signal of op-amp U3:A. The cutoff frequency is 2.091 *kHz*, meaning that the frequency of the signal below 2.091 *kHz* will be blocked and only pass the signal if it is above 2.091 *kHz*. Thus the signal of Figure 5.4 is filtered to smoother signal.

5.3 Electromagnet

The electromagnet generates magnetic field to attract the object. The force of attraction is equals to the weight to be levitated. The Equation 5.3 shows the force of attraction, F_m is:

$$H_{gap} = \frac{NI}{2\sqrt{a^2 + l^2}} \quad (5.2)$$

$$F_m = \frac{\mu_0}{2} H_{gap}^2 \times Area \quad (5.3)$$

Where μ_0 = permeability of free space; H_{gap} = magnetic field of the gap; a = radius of the gap; and l = length of gap.

From the Equation 5.2, the magnetic field strength (H) is directly proportional to the number of turns (N) and current (I) of the electromagnet. From the Equation 5.3, the force is inversely proportional to the air gap between the coil and the object, thus the object closer to the coil will result the stronger force of attraction.

In this project, the electromagnet is built by enameled copper wire of AWG 18. The number of turns is 1500 turns, the length of solenoid is 45*mm* and the radius of coil is 21.5*mm*. By applying the Equation 5.2, the coil magnetic field strength is:

$$\begin{aligned} H &= \frac{NI}{2\sqrt{a^2 + l^2}} \\ &= \frac{1500I}{2\sqrt{0.0215^2 + 0.045^2}} \\ &= 15038I \end{aligned} \quad (5.4)$$

The magnetic flux density (B) at the end of the coil is:

$$B = \mu_0 \mu_r H$$

$$= 4\pi \times 10^{-7} \times 100 \times 15038I \qquad (5.5)$$

$$= 1.89I\ Tesla$$

A graph can be plotted to show the magnetic flux density varies with the current based on the Equation 5.4.

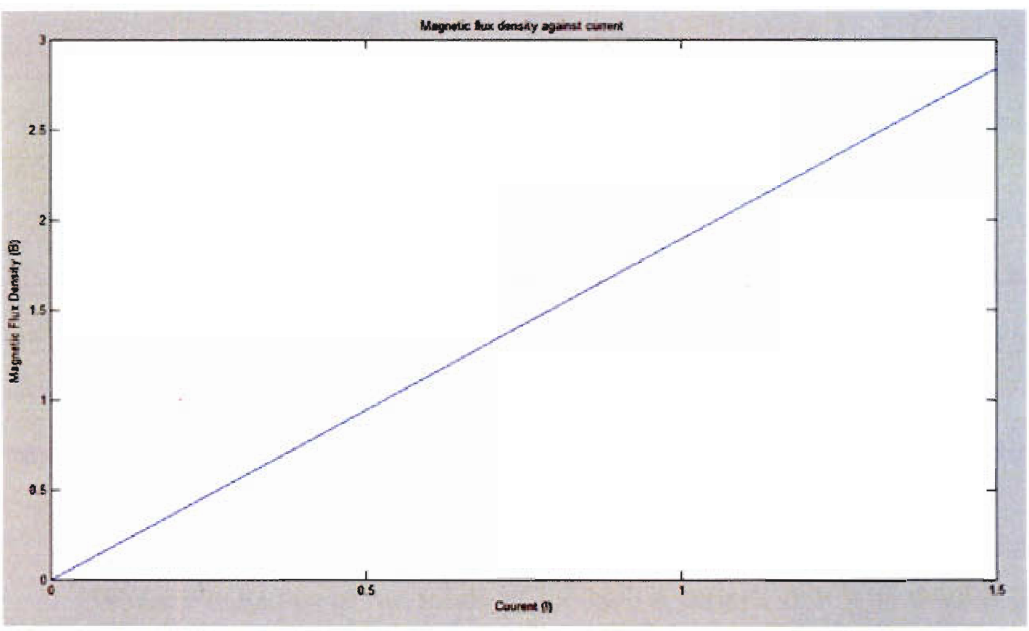


Figure 5.5 Magnetic flux density against current.

The magnetic field produces force of attraction to attract the object. In order to levitate the object, the force of attraction should be equal to the gravity force on the object. The gravity force on the 35 grams bolt is 0.34N. The force of attraction is calculated by Equation 5.3, which is 0.38N.

$$F = mg$$

$$= 0.035 \times 9.81$$

$$= 0.34N$$

$$Area = 0.163mm^2$$

$$H_{gap} = \frac{NI}{2\sqrt{a^2 + l^2}}$$

$$= \frac{1400 \times 0.90}{2\sqrt{0.0065^2 + 0.008^2}}$$

$$= 61.12k\ A/m$$

$$F_m = \frac{\mu_0}{2} H_{gap}^2 \times Area$$

$$= \frac{4\pi \times 10^{-7}}{2} \left(61.12 \times 10^3\right)^2 \left(0.163 \times 10^{-3}\right)$$

$$= 0.38N$$

Since the electromagnet is a multilayer multi-row coil, the inductance can be calculated by Equation 5.6 [18].

$$L = \frac{0.8\pi \mu_0 \mu_r r^2 N^2}{0.9r + l + d} \tag{5.6}$$

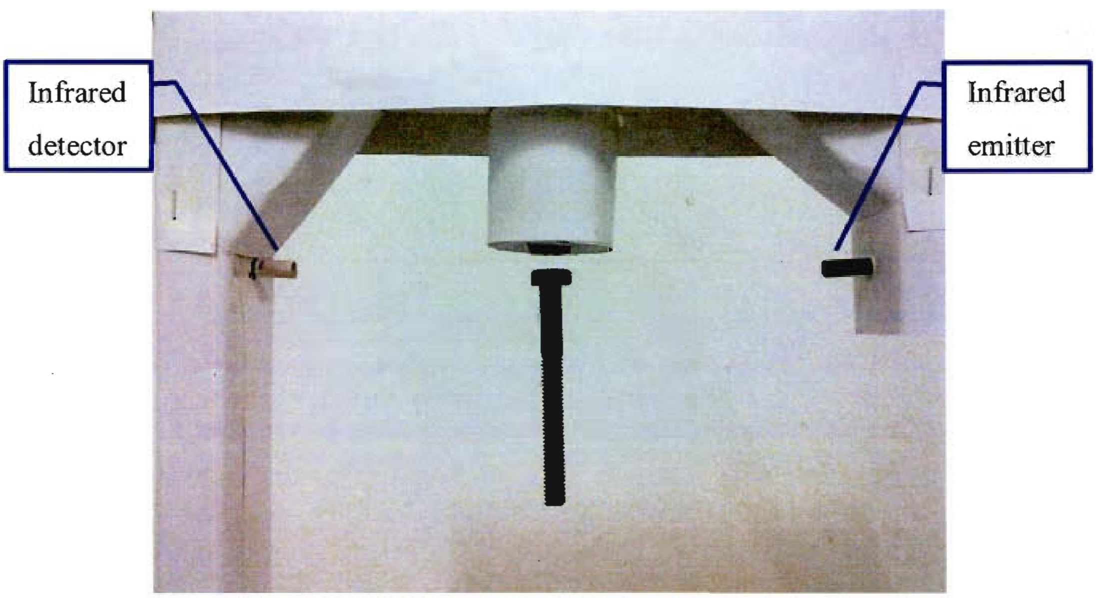
Where r = Radius of the inside of the coil in meters; N = total number of turns; d = depth of coil, and l = length of coil.

For the electromagnet had been built, the parameters are: r = 4.5mm, N = 1500, l = 43mm, d = 17mm and μ_r = 100Hm^{-1}. Hence the inductance of the electromagnet coil is:

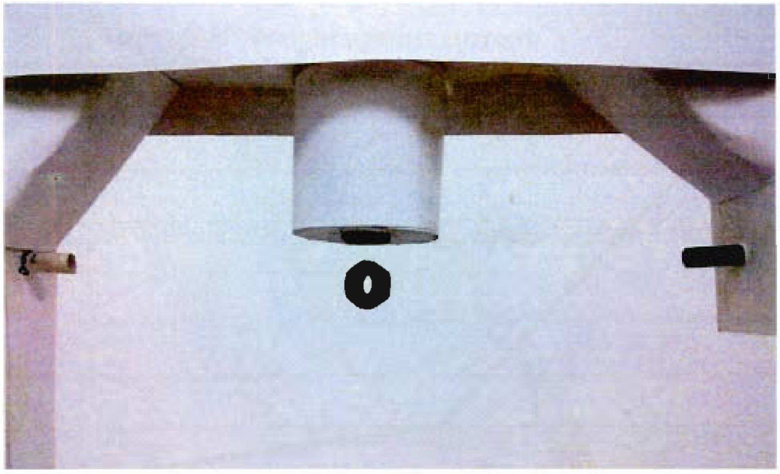
$$L = \frac{0.8\pi 4\pi \times 10^{-7} \times 100 \times (4.5 \times 10^{-3})^2 \times 1500^2}{0.9 \times 4.5 \times 10^{-3} + 43 \times 10^{-3} + 17 \times 10^{-3}}$$
$$= 224.67mH \tag{5.7}$$

5.4 Levitation Process

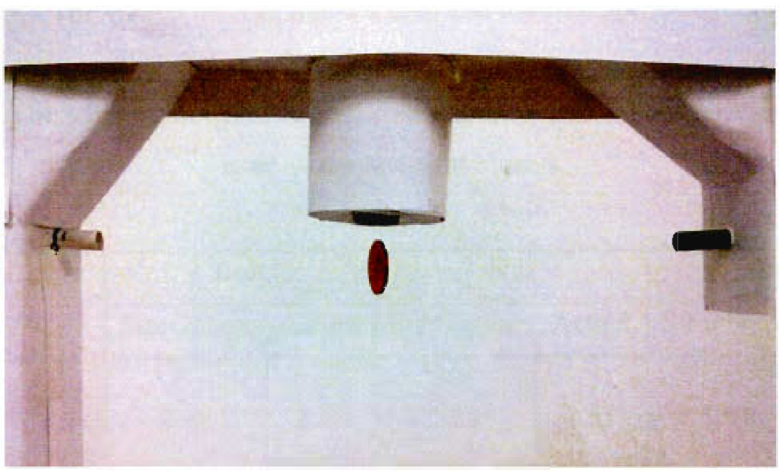
This project is designed of capable to levitate certain weight of metallic objects. The dimension of the objects should be in square or cubic size because of the infrared radiation is easily to be partially blocked by them and maintain floating at same position. The Figure 5.6 (a), (b), and (c) show the coil is able to float the three types of metals with stable even though the weight is different. The object such as the one cent as in Figure 5.6 (c) is not suitable to use in levitation because of the edge of the coin could not be partially block the radiation.



(a)



(b)



(c)

Figure 5.6 The bolt, nut and one cent coin are floating underneath the coil.

The bolt, nut and coin are levitating as shown in Figure 5.6 (a), (b) and (c). The coil current is recorded in the Table 5.1

Table 5.1 The weight of the three objects and the corresponding coil current.

	Bolt	Nut	Coin
Weight (*g*)	35	5	1
Current (*A*)	0.91	0.75	0.40

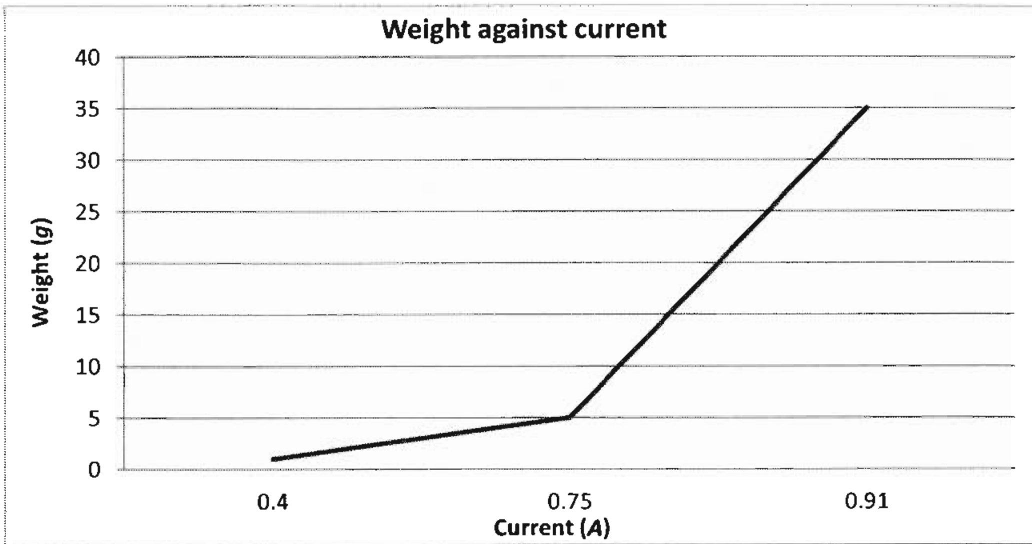


Figure 5.7 The weight of bolt, nut and coin and the corresponding coil current.

Table 5.2 The output voltage of several components when the bolt, nut and coin are used as the levitated objects.

Output \ Type	Bolt		Nut		Coin	
	Simulation	Actual	Simulation	Actual	Simulation	Actual
Infrared detector (*V*)	2.75	2.75	2.31	2.31	1.61	1.61
R-2R Ladder DAC (*V*)	2.73	2.70	2.30	2.28	1.60	1.60
U3:A (*V*)	5.46	5.40	4.60	4.56	3.20	3.20
Compensation Network (*V*)	13.9*m*	15.9*m*	11.7*m*	13.6*m*	8.1*m*	10*m*
U3:B (*V*)	4.66	4.17	4.01	3.58	2.94	2.62
Resistor R24 (*V*)	1.51	4.03	1.47	3.48	1.44	2.54
1N4148 (*V*)	0.81	3.58	0.78	3.04	0.76	2.10

The bolt shows in the Figure 5.6 (a) is used as the reference to analyze the effect of the weight of levitated object to the coil current. By attached load to the bolt, the result is shown at Table 5.3.

Table 5.3 The weight of object and the corresponding coil current.

Weight (*g*)	35	36	37	38	39	40	41	42	43	44
Current (*A*)	0.91	0.93	0.95	0.98	1.01	1.03	1.05	1.07	1.10	1.13

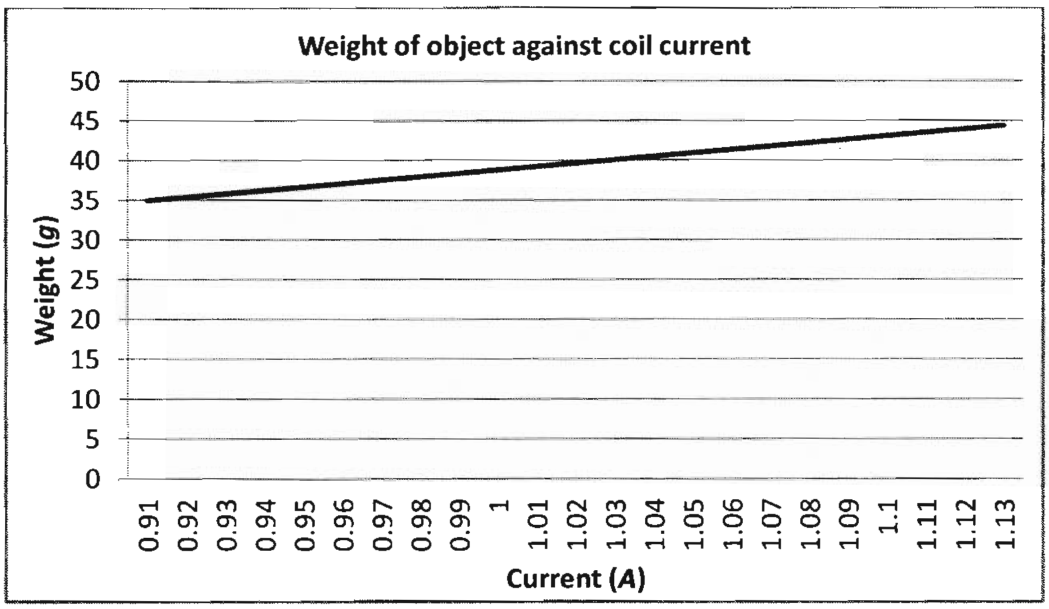


Figure 5.8 Weight of object against coil current.

5.5 Air Friction

One of the main reasons of applying electromagnetic levitation technique on trains is that the only friction working against it is between the trains and the air. This is proved by impart a bit of a spin to the levitated object and momentum will carry it for quite a long time. The Figure 5.9 shows a bolt is floating and spinning underneath the electromagnet while it is located in no moving air room. By apply a bit of force to spin it, the bolt takes 23 minutes to finish spinning. The time taken of the bolt to finish spinning is dependent of the surrounding conditions, the level of applied force, and the magnetic field strength. But this is proved that the air friction is very small.

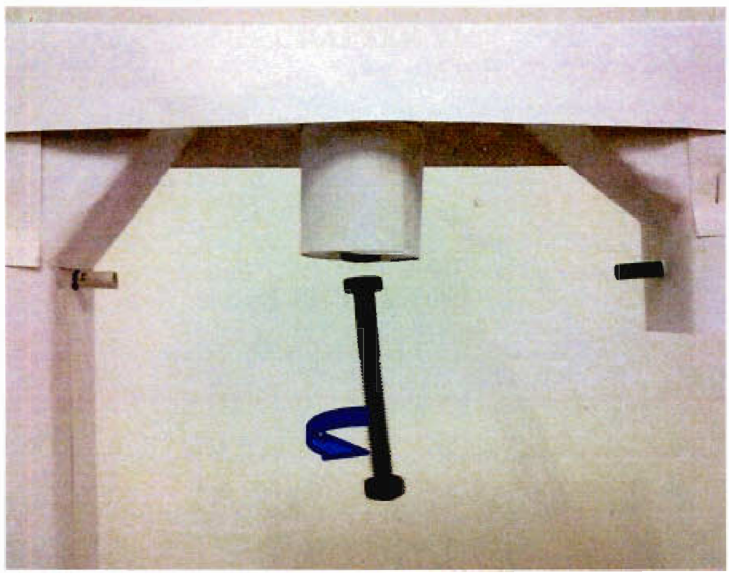


Figure 5.9 The bolt is spinning for a long time when a force is applied to spin it.

CHAPTER VI

DISCUSSIONS

This chapter will discuss the purpose of electromagnetic levitation established and the significant part of the project which comprises of the system stability, sensors, magnetic field, and the comparison between simulation and practical results.

6.1 Discussions

Electromagnetic levitation is a method by which an object is floating with no support other than magnetic field. The magnetic force is used to counterbalance the gravitational force onto the object. In some cases the lifting force is provided by magnetic levitation, but there is a mechanical support bearing little load that provides stability.

Electromagnetic levitation is used for maglev trains, magnetic bearings and for product display purposes. Maglev is a system of transportation that suspends, guides and propels vehicles, predominantly trains, using electromagnetic levitation from a huge number of magnets for lift and propulsion. This method has the potential to be faster, quieter, smoother and lesser power consumption than wheeled mass transit systems.

The big difference between a maglev train and a conventional train is that maglev train does not have an engine that pulls typical trains cars along steel tracks. The engine for maglev trains is rather inconspicuous. Instead of using fossil fuels, the magnetic field created by the electrified coils in the guide way walls and the track combines to propel the train. The trains are able to travel at up to 300 miles per hour. One of the factors that trains could travel at this very high speed is due to the only air drag against it.

This project is one of the technologies where the transport will be upgraded to be more useful and become up to date. The electromagnetic levitation concept will make the train become faster in this globalization era. This is helping to reduce the traffic jammed and also shorten time on travelling. This will benefit to citizens especially for urbanites.

The levitator circuit is supplied by two different voltage sources- one for the main circuit, and the other voltage source for the coil. The reason to separate the supplied voltage is that the coil will act as an inductor and become short circuit when the voltage is supplied to the coil. Thus the main circuit will not be fully functioning due to the short circuit of the coil.

A metallic object is placed in line with the sensors and the object will float and freeze as just underneath the coil. The LEDs and buzzer will be on to indicate there is an object is floating. This levitation process shows the system is stable. To maintain the system's stability the compensation network plays a crucial role to achieve it.

In order to achieve the system's stability, many experiments are done in the compensation network. The capacitance of C8 and the resistance of the parallel R18 and R30 as in the Figure 3.3 will give a cutoff frequency of 2.091 *kHz* to filter the signal or in other word to stabilize the feedback control system. Many trials are implemented to obtain this RC value. Other than this RC value may result the object flutter close to the coil due to the system is unstable.

The infrared diode of 880*nm* wavelength is used to emit infrared radiation when it is on. The radiation is invisible that cannot be directly sensed the light. This is because the wavelength of radiation is out of human capability. Human only can sense the light in between the band of approximately 400*nm* and 760*nm* wavelength. This band represents visible light. For infrared light, it is longer- wave radiation band that extends from the limit of eye sensitivity at 760*nm* to approximately 100μm [19]. One of the ways to sense the light is by the camera. The light is in purple colour.

The Equation 5.5 shows the magnetic flux density is 1.89 times the coil current. The Figure 5.5 is plotted based on the equation. From the graph, the magnetic flux density is increasing as the increasing of the coil current. The coil increases the magnetic flux to float the heavier object.

The coil has produced 0.38*N* force of attraction to counterbalance the 0.34*N* gravity force on the bolt. The magnetic flux density is normal to the interfaces between the air and the core. Since the core and the bolt cross sectional area are same, thus the bolt is used to calculate the forces. The force of attraction is always larger than the gravity force because of the loss of the magnetic flux.

According to the Equation 5.3, the attraction force is directly proportional to the surface area. This relationship is applied to levitation process that heavier object could be levitated by electromagnet if the top surface of the object is large enough to produce stronger attraction force between them.

The Table 5.1 shows the coil current varies with the 3 different weight of object. The Figure 5.7 shows the graph is not a straight line. The objects with different weight and surface area will result a disproportional coil current to generate magnetic field to float these objects.

The Table 5.2 shows the comparison between simulation and actual output for several components. The value of the output voltage of infrared detector indicates the detected intensity of light. The output voltage is increasing if the heavier object is levitated. This shows the stronger force of attraction produced by the coil is counterbalancing the heavier object.

The output voltages for most of the components have no distinct difference except for the R24 and 1N4148 output voltage. In simulation, the coil resistance is ignored, thus the 1N4148 output voltage is equals to the transistor base-emitter voltage. But in practical, the coil resistance existed, thus the 1N4148 output voltage is equals to the base-emitter voltage plus the coil voltage.

The Figure 5.8 shows the same surface area but in different weight of object will result the proportional coil current. The original weight of the bolt used is 35*g*. By attached load onto the bolt, the relationship between the weight of object and the coil current can be determined.

The Figure 5.9 shows a bolt is spinning underneath the coil. The bolt requires 23 minutes to finish spinning. This is obviously shows the spinning period is last longer than spinning it on the ground. This shows that the air friction is very small. The maglev train could travel up to 300 mph is due to the train is only experience the air friction. The turning without touching principle is also applied in motors to avoid abrasion of the brush.

The electromagnetic levitation technology is very useful in transportation so that it could save our time and also to help protect environment. It can be upgraded and commercial to public because it should be utilized widely to develop our technology.

CHAPTER VII

)CONCLUSION AND FUTURE RECOMMENDATION

This is the last chapter of the thesis that will conclude the overall of this project included the highlighted objectives. There is also contains the future recommendation to improve the project to be perfectly.

7.1 Conclusion

After completed this project, the main objective for this project which is to design the magnetically levitated hardware that works deals with the knowledge of electromagnetism has been done perfectly. The literature reviews of the process of induction magnet was implemented to success this project. Throughout completing this project, the programming is simulated by using simulation software that could send data to the switching circuit. Besides this, the circuit is developed in the printed circuit board and it is important that constructed with the suitable components. The system stability is a crucial point that levitate object at the desired position with stable. The oscillation of the object should be very small and not to be easily perceived. Finally the system is operated as expected to levitate metallic object. So, all of the objectives are achieved and the project is successful completed.

The levitation technology is useful in protecting our environment. The maglev trains consume lesser power than the conventional trains. Moreover, the maglev trains are operated by electricity while the latter are move by the diesel or generator that could harm the environment by expels poisoned gases to atmosphere.

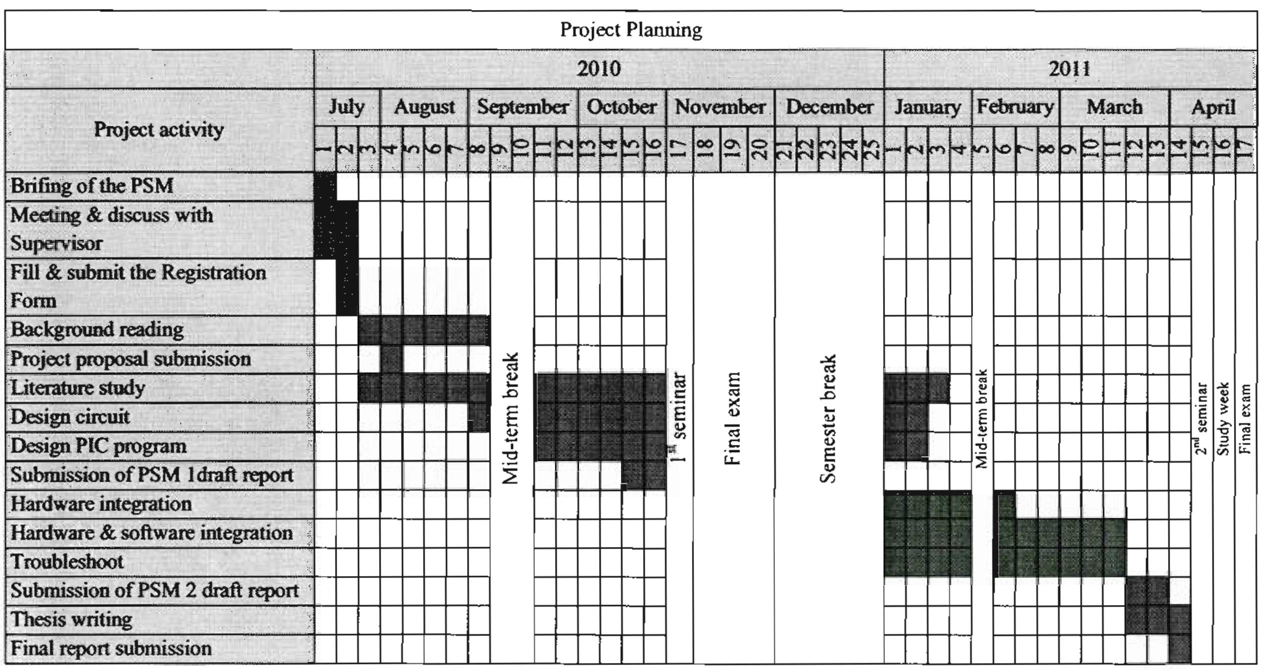
"Engineers are responsible to use their knowledge and skills to help protect the environment and also find solutions to the problems caused by modern technology," explained by Siva Kumar. Thus, the technology of electromagnetic levitation should be widely implemented to help protect the environment.

7.2 Future Recommendation

Nowadays, the urbanites prefer to choose trains such as the LRT or MRT to go to work or for travel in this globalization era. The electromagnetic levitation concept is very important to upgrade the status of these transports due to the low power consumption that give an effort in environment protection and also the higher speed of maglev may shorten the travel time.

Since the project is successful prove the concept of maglev, thus the project should be upgraded to build the maglev train prototype by using this concept.

GANTT CHART



Project Planning
2010
2011
Project activity
July
August
September
October
November
December
January
February
March
April
Brifing of the PSM
Meeting & discuss with Supervisor
Fill & submit the Registration Form
Background reading
Project proposal submission
Literature study
Design circuit
Design PIC program
Submission of PSM 1draft report
Hardware integration
Hardware & software integration
Troubleshoot
Submission of PSM 2 draft report
Thesis writing
Final report submission
Mid-term break
1st seminar
Final exam
Semester break
Mid-term break
2nd seminar
Study week
Final exam

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APPENDIX

REAL TIME DISTRIBUTED COMPUTER CONTROL FOR MAGNETIC LEVITATION

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ABSTRACT

This paper discusses the implementation of distributed computer controller for a magnetic levitation test-bed. Through this test-bed, the effectivity of the control system in real-time operation is shown. Using sensors to provide position feedback, the control system employs a closed-loop control in controlling the current through the electromagnet. Three PIC Microcontrollers are used as the computer control nodes of the system. For modeling, simulation and analysis of transient response,Steady-state error and stability of the control system, the MATLAB Toolbox Simulink is used.

I. INTRODUCTION

As machineries and electronic gadgets become more complicated, so does the need for new means of controlling these architectures with reduced risk of error, lower cost, greater accuracy, less time delay, and less failure. There are many existing control systems, most of which are of centralized control type. However, these are usually "communications intensive", which means that all instructions rely heavily on communicating with a central control. Hence, this type of control is vulnerable to failure. And when a centralized control system fails, every other part of the system being controlled is affected and will likely fail. Using distributed control would be a good alternative in designing control systems. Especially when the type of system to be controlled cannot afford to fail. With distributed control, there would be a chain or subtasks, which execute on different processors. Thus, there are controllers for every subsystem. Therefore, when one breaks, other subsystems may keep on going. Hence, the damage or disruption of the system may be kept at a minimum. This is certainly better than total failure of the operating system.

By embarking into this project, we would be able to make a modest contribution to the improvement of present control systems. This little development can benefit a lot of areas like aerial navigation, robotics, marine navigation, manufacturing, medicine, etc., which needs efficient control systems.

We chose to implement our thesis using a magnetic levitation setup. Making the hovering object stay at a certain position is a tricky and complicated process. In our case, an electromagnet is to be used to levitate a metallic ball. By adjusting the magnetic field strength of the electromagnet, we can make the ball float. However, the process requires a control system that is very accurate and fast that it would be able to control the position of the ball before it attaches itself to the electromagnet or falls to the ground.

By the end of this thesis, we should be able to:

- Simulate and implement a feedback controller in Simulink.
- Levitate a steel ball using electromagnets.
- Program a control software with very small or negligible delay for controlling a magnetically levitated steel ball.
- Implement a distributed control setup for the electromagnets of the magnetic levitator.
- Detect the position of the steel ball using position feedback from an infrared range sensor array and control its direction in a two dimensional (X-Y) plane by varying the current until the desired position is achieved.
- Interface a range sensor array and electromagnets to a target computer that will be used to implement lower level data acquisition and computer control.
- Provide a transient response, steady-state error and stability analyses of the control system.

II. SYSTEM CONFIGURATION

For the thesis to materialize, the system of the Real Time Distributed Computer Controller and the Magnetic Levitation test-bed has to be designed. Hence, for the designers to have general guidelines as to how the specific and complicated parts are to be constructed, a basic block diagram of the system has to be formulated. This is shown in Figure 1 with the details of each block to be discussed in detail later on.

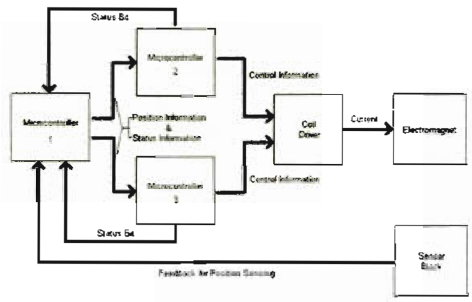

Fig 1. Block diagram of the System

In order for the group to construct an effective prototype of a distributed computer controller, a working analog model of the magnetic levitation test-bed would first be implemented. Then using the concept of how the ball floats in the analog controller, a simulation program will be formulated. It is from this simulator program where the design of the distributed computer controller will be based.

2.1 Stand-Alone Maglev controller

For us to be able to know how to design the digital control system of a Magnetic Levitation test-bed, a working analog, close-loop controller would first be constructed. Once a successful model is implemented, the concept of how it works would become the basis of the computer controller design. The circuit that was used in for the analog controller is shown in Figure 2. The success of a closed-loop circuit such as this depends heavily on the feedback system. In this setup, feedback is provided by a Photocell LDR. The variation in the resistance of the LDR causes the controller to adjust the current that is sent to the driver circuit.

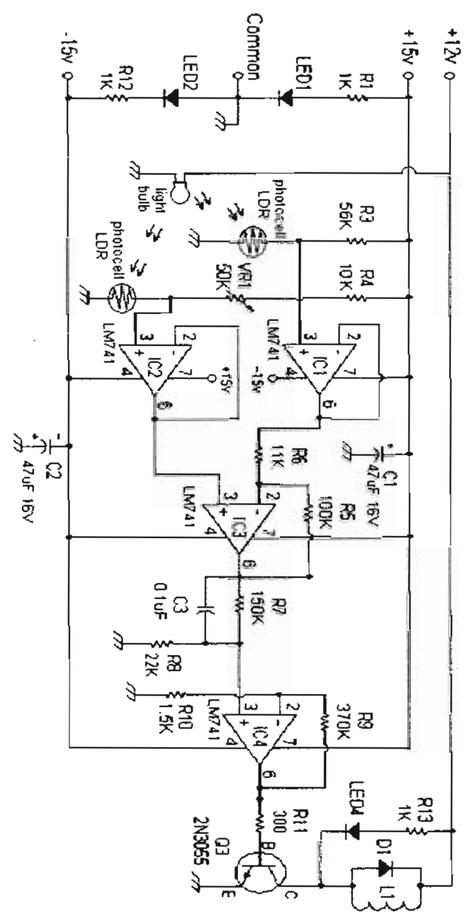

Fig 2. Analog controller of the Maglev test-bed

2.2 Ball control in two dimensions

In the setup of the maglev test-bed, the direction of the steel ball is controlled to stay at a certain point, with the factors in a 3D environment taken into consideration. The steel ball hovering at a certain point in free space can already be considered three-dimensional control. This is because levitation is achieved with the X, Y, and Z planes taken into consideration. Looking at Figure 3, it can be seen that in order for the system to have a 1 dimensional control or control at the Y plane, movement of the ball in the X and Z planes can be disregarded. The controller does not have to concern itself with the control of the X and Z path. Therefore, a see-through "guide path" can be utilized to keep the X and Z positions constant. Meanwhile, for the two-dimensional control in the X-Y plane, the controller does not have to concern itself with the control of the Z path. So just like in 1-dimensional control, "guide paths" (glass walls) can be employed to keep the displacement in the Z-plane constant. However, if this setup is applied to the magnetic levitation test-bed, there would be difficulty in placing the ball at the proper position during the start of each operation. To make the operating area of the test-bed more flexible, no "guide paths" were utilized. Hence, the control system was constructed for use in the 3D environment.

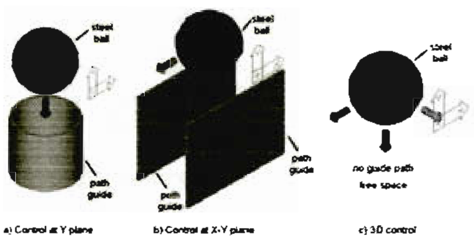

Fig. 3. Control operations of the steel ball at different planes

If two-dimensional movement (X-Y plane) is still to be introduced, a whole lot of complexity will follow and cause problems to the Maglev test-bed design. One of the biggest problems is on how to make the ball levitate fast enough to achieve stability, and from a moving position at that! As it would be later discussed from the simulation results, the electromagnet in itself has a characteristic, which enables it to have delay. The control circuit, no matter how fast and negligible the delay, can do nothing to improve the delay or response imposed by the electromagnet. In the working model of the Maglev test-bed in itself, the ball needs to be placed at the area of control from a stationary position. Moreover, it takes a long time (3 seconds at the fastest – for the actual setup) for the ball to start to stabilize and levitate. If movement is to be introduced, instantaneous stabilization has to happen. However, given the internal factor of delay in the electromagnets themselves, XY movement is just not possible for the current setup.

2.3 Simulink (Matlab) simulation program

Simulink allows for the modeling and simulation of a Magnetic Levitation Control System. Through simulation, we would be able to analyze the timing characteristics of the control system, which is impossible to do manually because of the very fast responses. Simulink has a user-friendly GUI. One can easily understand or interpret the written program because the code is shown in blocks allowing the user to easily understand the logic of the program. The main model layer of the generated Simulink program for the Maglev setup is shown in Figure 4. This upper layer serves as a general overview or block diagram of the entire system. Beneath each block are more subsystems that show a more detailed model of the tasks.

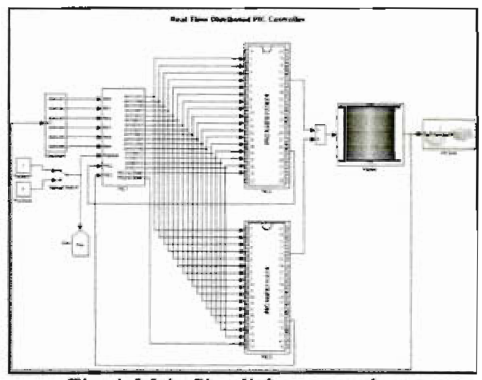

Fig. 4. Main Simulink program layer

One node or subsystem is labeled PIC1. This Subsystem is a representation of a Microcontroller, which is to be used in data acquisition and error detection. The data are acquired from a sensor array made up of six sensors. Then a switch indicates which position the controllers should use.

The two control nodes PIC2 and PIC3 are assigned with controlling different sets of actuators, which simulate coil drivers. PIC2 subsystem is concerned with controlling lower level actuators that are used to control the upper limit while the PIC3 subsystem is concerned with controlling the higher level actuators that are used to control the lower limit of the operating area.

X	X	1	1	1	1	1	1
Csb	Psb	Fb	Bbp 2	Bp2	Dsp 2	Dsp 1	Ulb

Fig. 5. Initial state 8-bit code

The subsystem PIC1 sends out 8-bit codes which contain control information for the two designated control nodes or subsystem. An example of this 8-bit code is shown in Figure 5, which indicates the initial state of the control system.

The first six bits of the 8-bit code are responsible for the position sensing of the steel ball. The Psb bit identifies the target positions, which are two predefined points in the Y-plane. This 8-bit code will be transmitted in the same medium where the control nodes will get the instruction data. With the control nodes (which in this case are PIC2 and PIC3) receiving the same data from PIC1, there has to be an identifier bit that would identify which controller will process the data and perform the required operation. The Csb or the Controller Select Bit performs the selecting operation. If the Csb is "0", PIC2 processes the data and executes the required operation. Then when the Csb is "1", PIC3 processes the data and executes the required operation.

2.4 Maglev controller using PIC

With the application of the simulated control system in Simulink limited, the proponents had to take a different approach in implementing the Real Time Distributed Computer Controller. Without the Real Time Workshop toolbox, which the group originally planned on using, Matlab cannot be interfaced with a working model of a Magnetic Levitation test-bed. However, buying the software would cost about P260,000.00. This is a very impractical approach since the research paper is just a student thesis and not for professional research. Moreover, the objective of this thesis is to model a distributed controller, which requires more workstations. Thus this setup could only become more expensive. Using the PIC Microcontroller is a logical choice as an alternative. Since a Microcontroller could already be considered as a computer in itself, the group could model a simple but effective Maglev controller. The PIC Microcontroller operates with the TTL or transistor-transistor logic. The input and output are set high at approximately 4.5 volts and low at a value almost 0V. Hence, amplifier circuits have to be attached to the Microcontroller to satisfy this requirement.

A good thing about the PIC Microcontroller is that it processes the instructions in very a high speed. Moreover, the processing speed can be varied by using crystal oscillators of different values.

$$t = 4 \times \frac{1}{f} \sec \qquad \text{(Equation 1)}$$

$$t = 4 \times \frac{1}{12MHz} \sec = 333.33 p\sec$$

A 12MHz crystal oscillator was used so that the system could have a very fast processing time. Since the program for the PIC has a cycle of about 50 instructions, then it would take 16.67μsec to do a task. During this time, the ball could only move 1.36nm (computed using Equation 1), which is insignificant considering the area of control for the Maglev test-bed is about 1.778cm in height.

2.4.1 Distributed Control Setup

From the simulation, we characterized the logic of how the actual hardware of the distributed computer controller should function. This logic is where the PIC-powered distributed controller based its operation. Its design and function are in most ways similar to that of the Simulink simulation. The block diagram of the system is shown in Figure 1. In analyzing the figure, the similarities of the prototype and the simulation program are accentuated. Like the Simulink program, the prototype also uses two control nodes, which in this case are in the form of PIC Microcontrollers, with another one used for data acquisition. Feedback is also provided by sensors and the system subject to control is also a Maglev test-bed. However, one noticeable difference is the lack of position selector in the prototype. This is because in the actual system, the direction control of the control system is geared towards keeping the steel ball at a fixed point. Moreover, it was realized from the analysis in Simulink that a change in position would be difficult if not impossible because the Maglev test-bed itself yields delay, which requires the control system to allocate a significant amount of time for the electromagnet to stabilize.

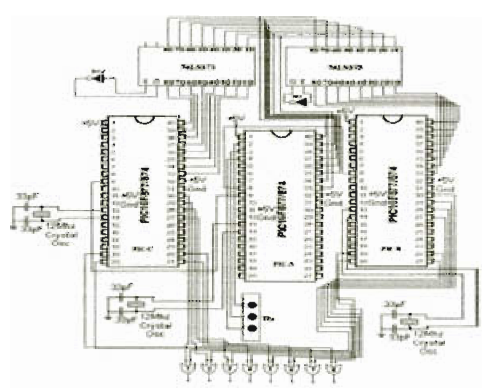

Fig. 6. Distributed control setup for PIC

III. DATA AND RESULTS

3.1 Simulation Results

Simulink allows for the modeling and simulation of a Magnetic Levitation Control System. However, in order for us to be able to gather the characteristics or information about our working model, we need the Real Time Workshop and xPC Target Workshop. Therefore, we were unable to gather data for different conditions in our actual model. We are limited to the data that we gathered from our simulation program.

Transient Response

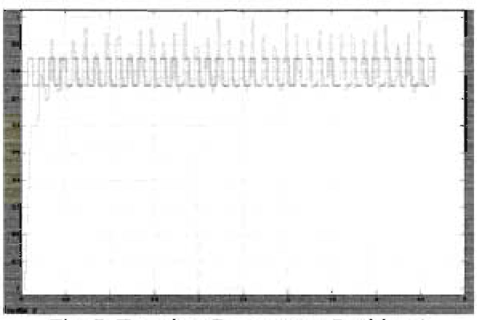

Fig. 7. Transient Response at Position 1

Figure 7 shows the blue waveform as the input signal to the electromagnet and the green waveform as its response. This figure shows that there is about 0.3 of a second delay before the electromagnet could actuate. It can also be seen that as the input signal rises, the output waveform rises but not instantaneously or not as fast as the input. Moreover, when the signal is high, it shoots up higher at about 0.1 in amplitude or double that of the input to the electromagnet.

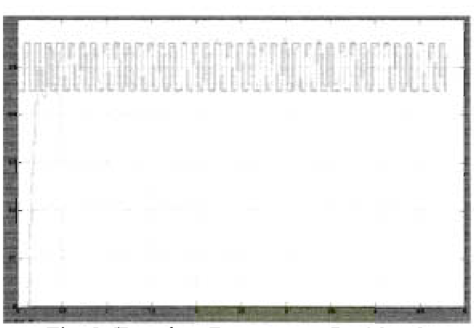

Fig. 8. Transient Response at Position 2

Figure 8 shows the blue waveform as the input signal to the electromagnet and the green waveform as its response. Similar to the previous condition, this figure shows that there is about 0.3 of a second delay before the electromagnet could actuate. It can also be seen that as the input signal rises, the output waveform rises but not instantaneously or not as fast as the input. Unlike the previous condition however, the output waveform is approximately of the same amplitude as the input to the electromagnet.

In the simulation for position one, the ball is nearer to the electromagnet. Therefore, the area of operation for this setup is lesser than that of position 2. That is why the difference in waveform from the input to the electromagnet to the actual output it projects in Position one is more noticeable than that of Position two.

Stability Analysis

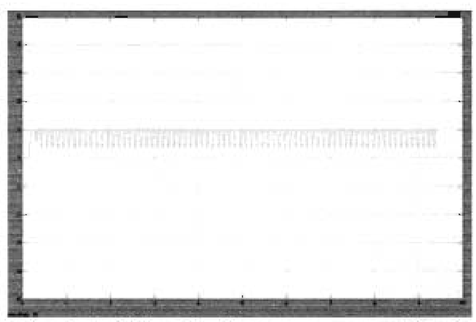

Fig. 9. Stability of ball movement at position 1

The figure above shows the position of the ball with respect to a specified time. The ball moves up and down with a distance of about 0.65 units. It can be seen that the up and down motion of the steel ball is constant after about 0.4 seconds onwards. Hence, the levitation of the ball is stable. It goes up until a certain position and then drops to a certain limit. It is also shown that the ball stays on the upper limit longer than it does in the lower limit. This is a normal characteristic of the motion of the ball. When the ball goes up and reaches the upper limit, it stops and then waits for the gravitational force to counteract the upward momentum. However, once it is going down and it reaches the lower limit, it could not afford to pause and wait for the electromagnet to counteract its downward momentum. It has to instantaneously be pulled up or else the ball will fall.

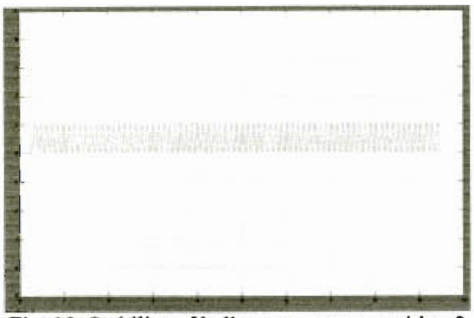

Fig. 10. Stability of ball movement at position 2

Similar to that of the previous figure, Figure 10 shows the upward and downward movement of the steel ball with respect to time. The ball moves up and down with a range of about 1 unit. It can be seen that the up and down motion of the steel ball stabilizes and becomes constant at about 0.4 seconds as well. After that, the range of operation does not change. Unlike in the previous setup however, the upper and lower limit ball movement in this position is almost the same. The time it takes the ball to go down from an upward motion is the same as the time it takes the ball to go up from a downward motion. This is possible because position two is situated at a lower point or is further from the electromagnet than position one. Therefore, the force of pull at a time right before the electromagnet turns off is lesser that if it were in position one. Hence, it would be faster for the gravitational force to counteract the upward momentum.

3.2 Actual Time Response

The data for the actual time response of the control system are taken from visual observations of the operation of the Maglev test-bed. The accuracy of the data however, is nowhere near the accuracy of the simulated response. This is because it is difficult to get time samples in milliseconds or microseconds then measure the displacement of the ball, which is in millimeters or even smaller units. Therefore, the only information gathered are the time before the ball starts to stabilize or float and how long before it falls down. A multitude of trials were taken, which unfortunately did not yield a recognizable pattern of operation. Therefore, it would be sufficient to present five trials in Table 1.

Since the data gathered look like they were numbers picked in random, meaning there are no recognizable time range for the levitation operation, there must be external factors that affect the operation of the Maglev test-bed.

Trial	Time to start To float (sec.)	Time for the Ball to fall (sec.)
1	8	10
2	6	2
3	2	10
4	2	29
5	12	11

Table 1

One of the external factors that might have the biggest effect is the lighting condition in the test-bed environment. To prove this theory, different experimentations were conducted to determine the effects of lighting condition to the levitation operation. From the natural color of brown, the test-bed background was changed to black. Because of the change in background, the lighting conditions changed. True enough, the ball operation changed. In this setup, the ball could not even be levitated. Although the light source has a constant intensity (12V bulb), the decrease in contrast brought about by the black background caused the system to not work. After this setup, the test-bed background was changed to color white. The color contrast increased with the background change. Therefore, levitation was achieved. However, the time of operation for the ball levitation still has no pattern. Sometimes it would fall within 3 seconds and sometimes it would stay afloat for as long as 17 seconds. Moreover, the fact that the ball falls down indicates that there are still external factors affecting the system, because in the simulation program, the ball does not fall. Hence, it could be assumed that a small change in light intensity causes instability, which leads to the ball drop. A solution to this is to supply a constant light source and take away the intensity variations brought about by the lighting of the outside environment (ambient light). However, the test-bed would have to be placed in an enclosed environment, which would make the setup not visible for observation. Another measure that could be taken is to put a shield on the sensor that measures the ambient light. This way, the light intensity variations brought about by the outside environment could be lessened. True enough, the operation of the test-bed with this innovation yielded the longest operating time for the floating ball.

Although the actual setup yielded different time responses, one thing certain can be observed – levitation cannot start instantaneously. The ball needs to be held at a stationary position from as long as 12 seconds or even as fast as 2 seconds, but not place it to the "areas of control" and instantaneously remove the support.

Once stability is achieved and the ball starts to float, it can be observed that the ball hardly moves, or if it does, the displacement is very small (maybe in terms of millimeters or micrometers) that it is not noticeable with the human eye. This means that instructions for control and adjustment of the current level are preformed at a very short period of time.

IV. CONCLUSION & RECOMMENDATION

Conclusion

During the early part the thesis work, the proponents were in a state of hopelessness as to how they were going to achieve the objectives that were set. As of the beginning of this term, a working model of a magnetic levitation test-bed has not been constructed yet. This was the application system for the Real Time Distributed Computer Controller. Moreover, in order for the group to program the controller, they needed to know the logic of how a steel ball would hover in mid-air without completely being pulled up into the electromagnet or without falling to the ground. Designing a controller for a system without knowing its operation is like shooting blanks during target practice at a shooting range. You'll never hit anything, much less the bull's eye. But then at the end of every tunnel there is light. It is then that the group realized a very important lesson, "Think outside the box." After extensive testing on one approach that does not work, it was decided that another approach would be taken. The idea that the ball will float with the use of two electromagnets at opposite ends pulling the same steel ball was finally put to rest. The group has come into a realization that magnetic fields are not like rope with which could be tied up to an object and pulled from opposite directions to make a steel ball stay at the middle. For the second approach, the proponents tried to levitate a ball with polarity by putting small permanent magnets at opposite ends of a hollow plastic ball. Again, using two electromagnets, different combinations of attraction and repulsion were tested but every try still failed. Like that of the first setup, steady-state was not achieved. For the next approach, a single electromagnet with varying force of attraction was used. But first, an analog controller was used. Through this setup, it was realized that levitation can be achieved by placing an electromagnet on top and varying the current supplied to it. In this setup, steady-state was achieved. The steel ball will levitate by controlling the magnetic force of the Maglev test-bed. The stability of the system could be maximized by making the environment of the experiment to be as controlled as possible. External factors like varying ambient light, wind blowing and vibration of the test-bed can disrupt the stability of the system.

The simulation results of the Simulink program showed that position control of the steel ball is not possible. The transient response shown in Figures' 7 and 8 showed significant delays of about 0.3 seconds at the start of implementation of both positions. Hence, if position is changed while in simulation or while the ball is already hovering at one position, the ball will completely fall to the ground or stick to the electromagnet. The source of error here is not to be blamed on the control system for its processing speed is more than enough to do the tasks within the ideal time period. The simulation results indicate that the electromagnet itself has a noticeable delay. Hence, even if the control system is real-time, there still has to be extra time allocated for the steel ball to stabilize and float successfully. This makes ball movement or change in displacement in two dimensions (X-Y plane) not possible. However, two-dimensional (3D even) control is still achieved by controlling the direction of the ball to stay at a certain point in free space. Also, the effectiveness of distributed controller in the levitation of the steel ball, which is the main objective of the thesis, could already be clearly shown.

The process of levitation in itself is time critical. A slight error or delay in giving and executing instructions would result to a catastrophic system failure. Moreover, the group was able to clearly show the importance and effectiveness of distributed control with simplicity through the magnetic levitation test-bed that was constructed. The upper limit was controlled by one node and the lower limit was assigned to another. The distribution of tasks was still implemented. Hence the failure of one controller node produced minimal error compared to a full system shutdown if central control was implemented.

Since levitation using an analog controller has already been achieved, it means that an equivalent digital controller can be designed.