MOBILE ROBOT

by

ABU MASNUR ABU KASSIM

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the

Electrical & Electronics Engineering Programme

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in partial fulfillment of the requirement for the

BACHELOR OF ENGINEERING (Hons)

(ELECTRICAL & ELECTRONICS ENGINEERING)

Approved by,

(AP Dr Mohd Noh Karsiti)

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.

ABU MASNUR ABU KASSIM

ABSTRACT

The essential components for a mobile robot include environment sensors, navigational intelligence and actuators (wheels or legs). The mobile robot to be developed in this project incorporates ultrasonic proximity sensors input devices as environment sensors and two motors (which control the wheels) as actuators. The main goal of this mobile robot is to avoid collisions with obstacles or walls and plan its paths around them for subsequent runs.

A transmitter-receiver pair is used for the ultrasonic sensor circuitry. The transmitter mainly consists of a 555 timer and is controlled by an external device (microcontroller) to initiate pinging sequences. The receiver is primarily made up of LM741 Op-Amp, LM567 tone decoder, and LM311 comparator. The LM741 is used to amplify the received signal while the LM567 is used to filter and detect only the preset frequency. The LM311 comparator is used to minimize false triggering emanating from power surges in the supply current.

An H-bridge circuit is used to control the motors' forward/reverse motion via its 2 bit binary inputs at its strobes. The H-bridge circuit utilizes Darlington-Pair transistors and diodes to control the forward/reverse current flow to the motor.

A PIC16F84 microcontroller is used as the brain of the mobile robot. The main function of the microcontroller is to initiate ping sequences to the ultrasonic transmitter, measure the time for the ping echo to return, and decide to move forward, turn or reverse the robot accordingly. Extended functions of the microcontroller is to create a 2D terrain map, and plan its path to any specified target point. These are to be achieved by Voronoi Diagram or Delaunay Triangulation method for mapping, and a combination of one or more of the Dijkstra, Bellman, Ford, Moore, Johnson, Floyd-Warshal, or A* algorithms for best path calculation.

In some parts of the project especially the intelligent navigation algorithms, the author encountered many new ideas and theories which the author cannot fully understand. It is hoped that future projects will emphasis on these areas.

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ABBREVIATIONS AND NOMENCLATURES

ABS Antilock Braking System

AGV Automated Guided Vehicle

AI Artificial Intelligence

ANN See *Artificial Neural Networks*

Artificial Neural Networks A type of artificial intelligence based on the concept of the brain working mechanism

Boolean Logical true or false

Crystal A quartz device that operates on the piezoelectric effect and exhibits very stable resonant properties

DC Direct Current

Fuzzy Logic A type of artificial intelligence which caters for a region between true and false by providing the truth or false percentage membership

IC Integrated Circuit

IEEE Institute of Electrical and Electronics Engineering

Noise Unwanted signal

Op-Amp See *Operational amplifier*

Operational amplifier A type of amplifier that has very high voltage gain, very high input impedance, very low output impedance, and a good rejection of common-mode signals

Oscillator An electronic circuit based on positive feedback that produces a time-varying output signal without an external input signal

PLC Programmable Logic Controller

CHAPTER 1
INTRODUCTION

1.1 Background of Study

The creation of Aibo (Robot Dog) by Sony and Asimo (Humanoid) by Honda marked a new era of robotics. Although not the first, they are the most publicized robots to date.

Robots and robotics (in process automation) have been in the industrial arena for a long time. The replacement of hardwired logic with PLCs and microcontrollers a few decades back has expanded the capabilities of such robots. Robots have become much smarter and much faster than before. Before long, researchers began to show interests in "taking the robots out of the industries". They began creating robots which are mobile. Most of these robots try to imitate a certain animal, the most popular one being the ant. Other robots are designed to imitate animals in so many other ways to perform tasks such as swimming, climbing, crawling, and running. Conventions and symposiums have been held to gather enthusiasts together and to share ideas of their design.

Path planning has been an important issue in mobile robots. The main aim for most heuristic path planning is to find the shortest path or shortest time to reach a certain goal, while avoiding obstacles along the way. Path planning makes use of the many mathematical algorithms which has been discussed since a century ago. Starting from path mapping which involves the use of Voronoi-Delaunay diagram, path planning extends to the use of path finding algorithms such as Dijkstra's *greedy* approach, Bellman-Ford-Moore, and Floyd Warshall.

The emergent of AI and the advancement in microcontrollers/microprocessors has initiated fascination among robot enthusiasts. They began including AI to their design; fuzzy logic, artificial neural networks (ANN), and genetic algorithm being the most prominent. Communications are also embedded in their design, mostly to enable monitoring or controlling remotely via a computer.

1.2 Problem Statement

The purpose of this project is to build a simple robot with minimal capability of navigation. The robot will need to incorporate motor control, sensors, and a logic controller to achieve this.

A power supply unit is to be designed to power the circuitry. Among options available are normal regulated (wired) power supply, sealed rechargeable lead-acid battery and rechargeable battery pack.

In terms of mechanical design, a prototype will be built to display its navigational capabilities. As such, a simple design consisting two (2) separately controlled motored wheels and a flywheel to balance the unit is to be constructed.

These designs will perform as the basis for testing and improvements for future researchers.

1.3 Objectives and Scope of Study

The main aims of this project are as follows:

- to research on the various input sensors possible for a mobile robot
- to select a suitable motor type for ease of control
- to experiment with the various ways of control via programming of the microcontroller
- to enhance the capability of the basic robot by incorporating communications or interface to a computer or remote controller
- to enhance the physical design of the robot to improve stability and practicality

The scope of study covers the following areas:

- **Navigational Planning System** – There are three types of to be studied and chosen from, depending on the type of navigation chosen. The three classical types of navigation systems are "(i) Obstacle Avoidance, (ii) Path Traversal Optimization, and (iii) Time Traversal Optimization".[1] Voronoi path mapping technique have to be studied, and suitable path planning algorithm(s) must be decided upon.
- **Sensory System** – The most basic sensors can be divided into three types. The first utilizes ultrasonic waves to estimate the distance of an obstacle. The second is the tactile sensory system which involves physical contact of the sensor with an obstacle. The third sensor utilizes light in the form of infrared to detect obstacles.
- **Mobility** – Common mobile systems used are wheels and legs. In this project, wheels will be used as it is the simplest and most stable for smooth terrain type.
- **Communication System** – Communications is important to link the robot to the outside world. Communications serves as a means of controlling or sending commands to the robot, and to enable the robot to report back. Communications also allow certain processing tasks to be performed off-board by simply transmitting input data to a more capable system such as a computer and receiving the processed instructions for execution. The scopes to be studied in the communications system are wireless communication and digital data communication. Several standards must be followed to ensure non-interference and compliance with federal law or IEEE standards.
- **Power System** – Power sources suggested for this project are regulated power supply unit and rechargeable battery. The former will be used in early researches while the latter in the final design. For ease of use, a single source power supply is to be designed. Thus, a circuitry will be designed to supply power at different voltages for the different needs by the motor and the ICs. Solar cells will also be considered, although it is doubtful that it can provide enough power for the motors.

CHAPTER 2
LITERATURE REVIEW AND/OR THEORY

2.1 Definition of Robot

There is no specific definition of a robot. Joseph Engelberger, a pioneer in industrial robotics, once remarked "I can't define a robot, but I know one when I see one" [2]. Robot enthusiasts, however, define robots as a body moved by a reprogrammable brain (computer). The inclusion of "reprogrammable brain" in the definition separates robots from other movable machines such as cars. A simpler definition of mobile robot is "an electromechanical device able to navigate itself and perform specific tasks".

A locomotion (mobility) system is one of the most important aspects of a mobile robot. Wheels or tracks are the best choices if the robot only needs to move on smooth ground. Bigger wheels can also be used for rougher terrains. However, designers often use legs instead, because they are more flexible and help researchers understand natural locomotion.

2.2 Ultrasonic Proximity Sensors

Ultrasonic waves are sound waves which are inaudible to human ears. The typical frequencies of ultrasonic sensors range above 20kHz. The speaker (transmitter) and the microphone (receiver) are called transducers. Normally, both transmitter and receiver are built into one transducer to transmit as well as receive the ultrasonic waves. Most ultrasonic sensors operate at frequencies between 40kHz and 250kHz.

Ultrasonic sensors are mainly used as motion, presence, proximity, or distance measurement sensors. The basic principle in ultrasonic sensors is the transmission of short bursts of sound waves and the detection of its echo reflected by the presence of an obstacle. A proximity sensor will calculate the time for the echo to return to determine the distance of the obstacle.

As a sound wave, the ultrasonic requires a medium to traverse and will not work in vacuum. Ultrasonic proximity sensors are affected by various factors:

- Temperature
- Transmission medium
- Wavelength
- Attenuation due to the medium properties
- Background noises
- Transmission direction and reflection angle
- Size of obstacle
- Sound absorption property of the obstacle

Formula Related to Sound

An ultrasonic proximity sensor transmits short bursts of pulses and measures the time taken for the echo to the receiver. The calculation of the distance of an obstacle is then calculated using the time taken and the speed of sound in the specific medium. The accuracy of the computation is related to the accuracy of the speed of sound used. The speed of sound, in turn, is affected by both temperature and composition of the medium. A simplified formula to calculate the speed of sound in air as a function of temperature is given as follows:

$$c(T) = 326{,}100\sqrt{1 + \frac{T}{273.15}}$$

where,

$c(T)$ = speed of sound in millimeters per second

T = temperature of the air in °C

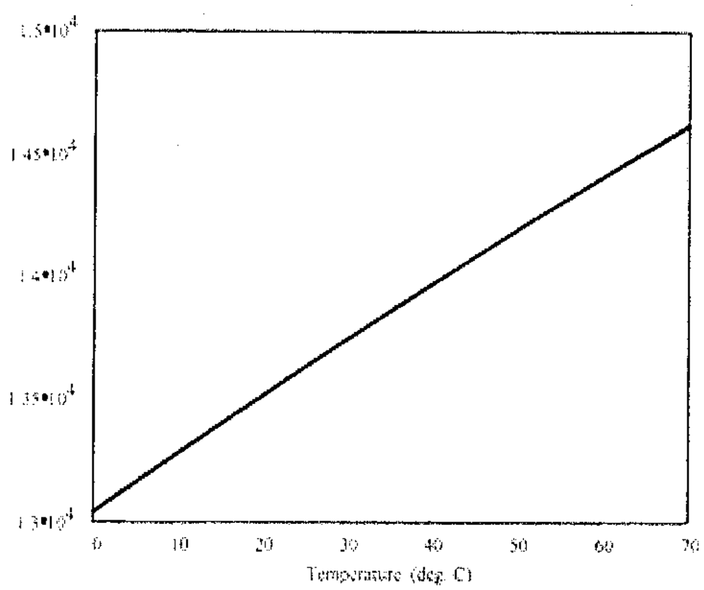


Figure 1 : Speed of Sound vs Temperature [3]

Friction losses in transmission medium reduce the amplitude of sound pressure as it travels. The attenuation affects how far the sound can be detected before it is overwhelmed by noise. In air, attenuation is mainly affected by two factors, namely the frequency of sound and the humidity of air.

An ultrasonic sensor needs to function within a wide range of attenuation, depending on the specific requirements. A good rule of thumb is to calculate the maximum attenuation to ensure usability of the sensor. A good approximation of the maximum attenuation level for normal room temperature and frequencies up to 50kHz can be attained using the following formula:

$$\alpha(f) = 0.01f$$

where,

$\alpha(f)$ = maximum attenuation in dB/ft

f = frequency of sound in kHz

As noted, the maximum attenuation varies with frequency. As a rough guide, for frequencies above 125kHz, the maximum attenuation occurs at 100% RH, while at 40kHz, the maximum attenuation occurs at 50% RH.

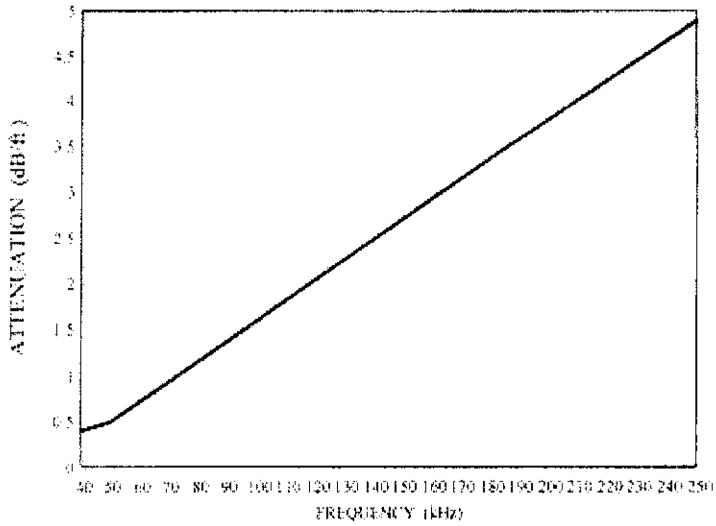


Figure 2 : Maximum Attenuation of Sound at Room Temperature vs Frequency [3]

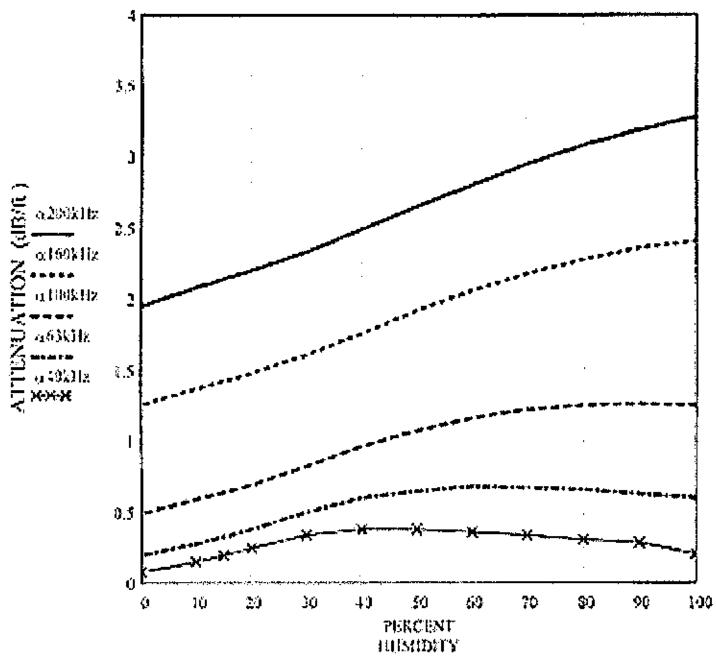


Figure 3 : Attenuation of Sound at Room Temperature vs Humidity [3]

A sound wave reflects similarly to a light (electromagnetic) wave. The echo level is determined by the distance of the reflector, its size, and its absorption property. To reduce the complexity of the calculation, we may assume that the size of obstacle is large enough to reflect the entire beam and exactly perpendicular to the source. Thus, the following formula stands:

Spreading Loss = 20 log (2R),

Absorption Loss = 2αR

Where R is the distance between the transducer and the obstacle and α is the absorption constant of the reflecting surface.

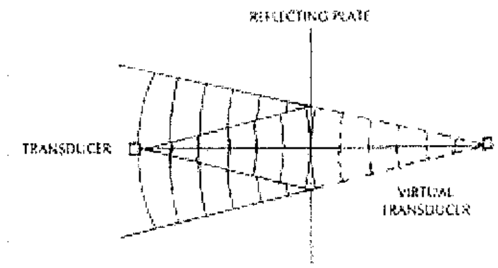


Figure 4 : Echo From Flat Surface [3]

2.3 Motor

A servo motor is controlled by PWM (Pulse width modulation) signal, whereby the angle of the motor is controlled by the length of signal it receives every predetermined intervals (set by manufacturer). The following diagram shows some examples of turning angles for specific pulse duration for an anonymous servo motor with 2ms pulse intervals (500Hz):

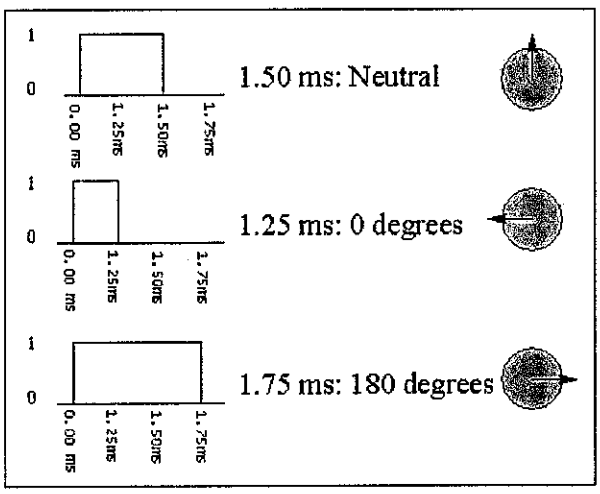


Figure 5 : Pulse Width vs Angular Displacement [4]

A servo motor has also the advantage of acceleration control, whereby the acceleration/deceleration of rotary speed and the torque delivered are determined by the angle it has to move and the load it has to carry. Hence, the power consumption of a servo motor relies on the load. A servo motor has a limitation in the maximum angular displacement set by the manufacturer by means of internal stoppers.

Stepper motors have fixed angular movements as compared to linear angular motion which is the case of servo motors. The angular displacement spacing is determined by the number of poles in the motor. Stepper motor has a trade-off between speed and torque. When speed is increased, torque is reduced, and vice versa.

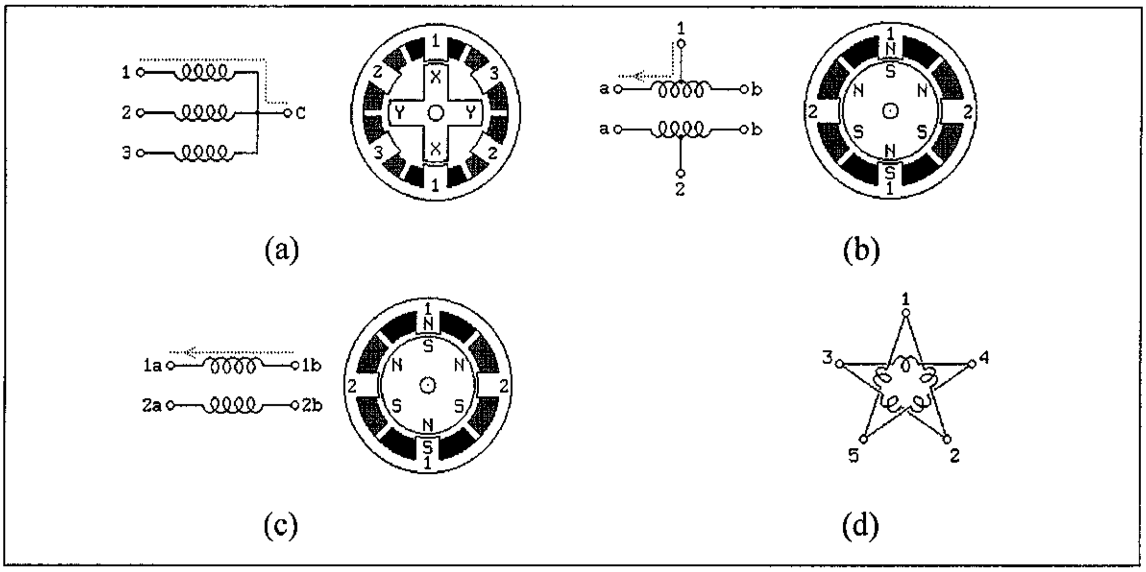


Figure 6 : Various Types of Stepper Motors, (a) Variable Reluctance, (b) Unipolar, (c) Bipolar, and (d) Multiphase Stepper Motor [5]

DC motors do not provide angular control. Some of the available DC Motor configurations for self excited field wounds are presented as follows:

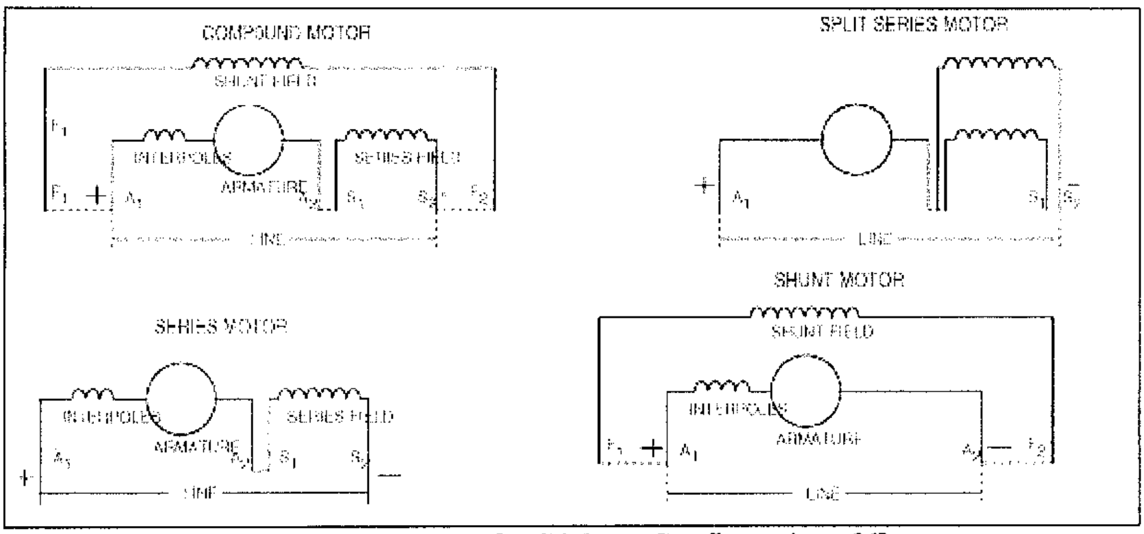


Figure 7 : Types of DC Motor Configurations [6]

The speed and torque characteristics at different current are represented in the following figure:

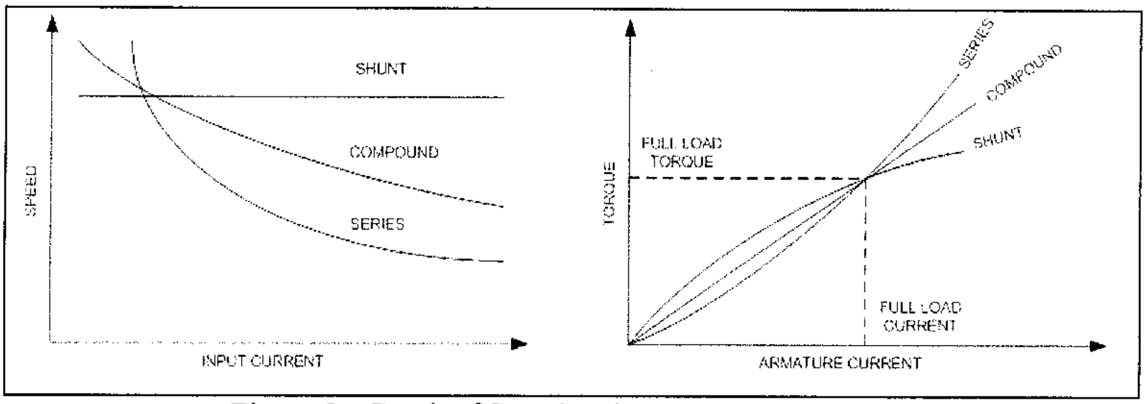


Figure 8 : Graph of Speed and Torque vs Current [6]

Where stability in speed is required, the shunt motor is most desirable, whereas for torque linearity, a compound motor is the best. The calculations for the speed, torque and flux can be derived from the following equation:

$$N_r = \frac{V - I_a R_a}{k\Phi}$$

where,

N_r = rotation speed

Φ = magnetic flux

2.4 Navigation System

Fuzzy Logic

Fuzzy logic works on the concept of membership function of a particular data. Although similar to probability in concept, fuzzy logic is not the same as probability. A probability expresses the likelihood of something to be true, while fuzzy logic expresses the truthfulness of a data. Fuzzy logic provides relaxation between true and false in the traditional Boolean logic. As such, it is considered as the superset of the Boolean logic. Fuzzy logic may be expressed as a fraction between 0(false) and 1(true), or as a percentage of membership.

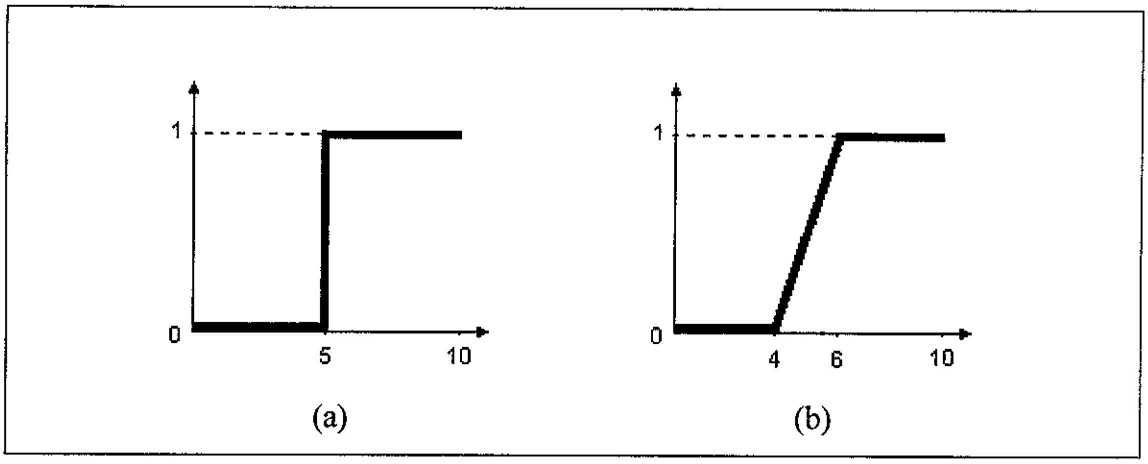


Figure 9 : Comparison Between (a) Boolean Logic, and (b) Fuzzy Logic

Hedging is used as modifiers to a certain fuzzy set. There are four techniques of hedging:

- Approximating
- Complementing – inverting a fuzzy set
- Diluting – expanding a fuzzy set
- Intensifying – compressing a fuzzy set

Path Mapping Methods

Voronoi Diagram / Dirichlet Tesselation

The first discovery of Voronoi diagrams were in the year 1850 by a mathematician named Peter Lejeune-Dirichlet. Only in 1908 were these diagrams written about in a paper by Voronoi. The Voronoi cells/polygons are therefore sometimes also called Thiessen Polytopes or Dirichlet Regions.

A Voronoi diagram is a geometric representation of boundaries which are equidistance from two or more sites. The Voronoi diagram is therefore useful to draw paths of a mobile robot. The sites in the case of a mobile robot may be walls or obstacles. The following diagram clearly depicts the idea:

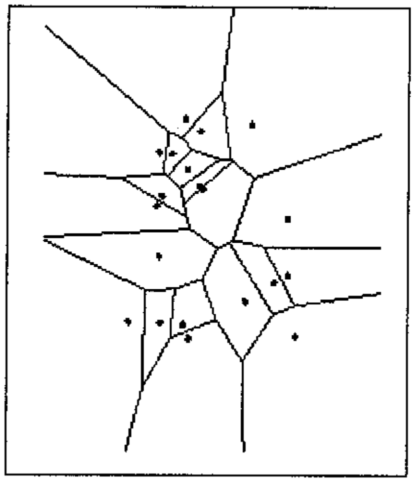


Figure 10 : Voronoi Diagram [7]

Voronoi diagram can be constructed using various approaches. A popular approach is the incremental algorithm. The incremental algorithm adds a new site to an already existing diagram. Steve Fortune further developed a plane-sweep algorithm in 1985 which is more efficient than any incremental algorithm.

Delauney Triangulation

Delaunay triangulation is a collection of edges of a point set which satisfies the "empty circle" property. For each edge we can find a circle containing the edge's endpoints but not containing any other points.

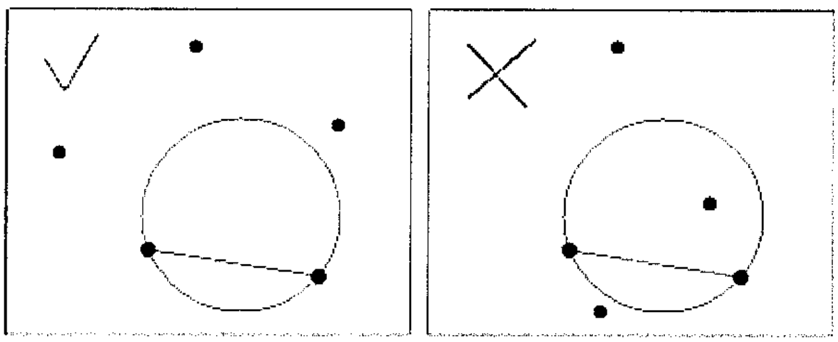


Figure 11 : Delaunay Triangulation [7]

The Delaunay triangulation is the dual structure of the Voronoi diagram in R^2. By dual, we mean to draw a line segment between two Voronoi vertices if their Voronoi polygons have a common edge, or in more mathematical terminology: there is a natural bijection between the two which reverses the face inclusions. The circumcircle of a Delaunay triangle is called a Delaunay circle. [7]

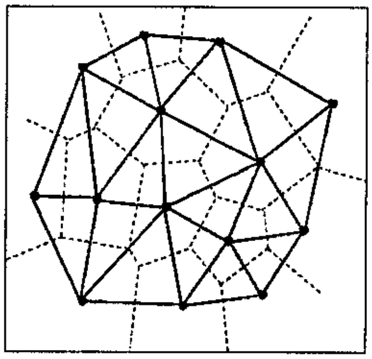


Figure 12 : Voronoi Diagram (dotted) and Delaunay Triangulation (solid) [7]

Path Finding Algorithms

Dijkstra's Approach

Dijkstra's algorithm uses a *greedy* approach in order to find the least cost path to its destination. For example, let us assume a starting point A. To reach a certain destination Z, there is a certain mesh of straight routes connecting A to Z via B to Y nodes or juctions. Each of the nodes or junctions may be labeled with its distance to Z. By using Dijkstra's algorithm, the determination of which node to follow next is determined by the adjoining nodes which has the shortest distance to Z. This approach however may end up with an error when the selected node is a cul-de-sac (dead end). This approach is also known as the best fit approach. As the calculations involve the knowledge of the distances beforehand, the Dijkstra algorithm is considered a heuristic approach.

Bellman-Ford-Moore

A Bellman-Ford-Moore algorithm allows a certain junction to be preferred although it may take a longer distance. This is done by assigning a negative distance to the node. Using the Dijkstra approach will cause the preferred path to be infinitely preferred. With the Bellman approach, the length of each path connecting to the next node plus the distance of the next node becomes the weight. This algorithm is also a heuristic approach.

*A**

This algorithm is a combination of a few basic concepts of path finding. A combination of blind search, heuristic approach, Branch and Bound, dynamic programming, and underestimates produces the A* algorithm.

A blind search is a search for the first possible path to the predetermined destination. From a start node, the path is extended to all the neighbouring nodes. These paths are stored in memory. Each of the extension is then extended again to its respective neighbouring nodes. Upon detection of a repetition of the same node in the same path, the node is eliminated. This avoids cyclic and reverse paths. The process continues until one path reaches the destination. If there actually exist a path, the blind search is guaranteed to find it.

The blind search does not necessarily end with the shortest path, since the distances between nodes are not accounted for. Plus, to store all the possible paths along the way will require a large amount of memory. With a little heuristic knowledge of the path distances of each node to the destination, the Dijkstra algorithm is implemented. The memory is then used to store only the current path and discard the rest. This saves the amount of memory being used. However, there is a possibility that a path is not found, whereas there actually exists one, as has been discussed earlier.

Branch and Bound is a method which utilizes the distances between nodes. It starts of similar to the blind search, except that it only expands the shortest path nodes until the possible end (by always rearranging the shorter path at the top of memory). If it finds one, it will save it and start searching for a second route. After each extension to the next node, if it finds that the path exceeded the length of the first route, the route will be discarded and another search begins until the shortest route is found. An example is as follows:

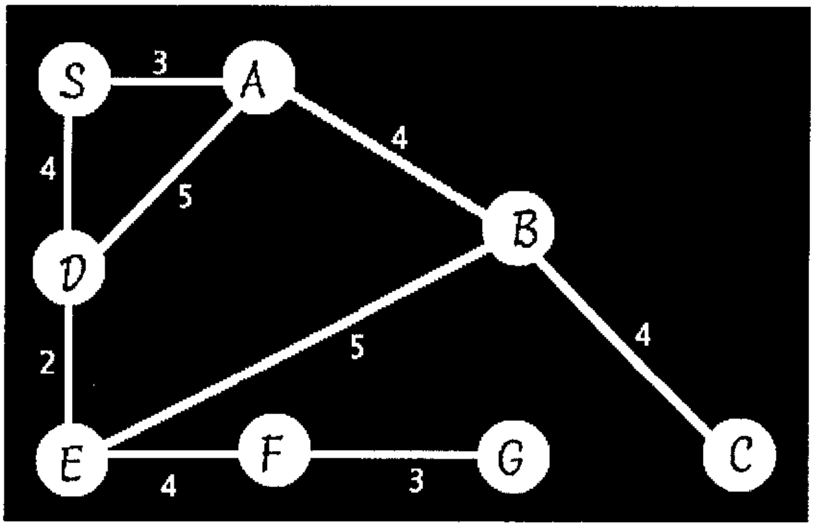


Figure 13 : Branch and Bound Example [6]

For the given figure, the steps taken will be as follows:

Table 1 : Branch & Bound and Underestimates

Step	Memory Location	Path	Remark	Underestimates
1	M0	S-A (3)	Expand next	3 + 10.4 = 13.4
	M1	S-D (4)		4 + 8.9 = 12.9
2	M0	S-D (4)	Expand next	
	M1	S-A-B (7)		
	M2	S-A-D (8)		
3	M0	S-D-E (6)	Expand next	12.9
	M1	S-A-B (7)		
	M2	S-A-D (8)		
	M3	S-D-A (9)		19.4
4	M0	S-A-B (7)	Expand next	
	M1	S-A-D (8)		
	M2	S-D-A (9)		
	M3	S-D-E-F (10)		
	M4	S-D-E-B (11)		
5	M0	S-A-D (8)	Expand next	
	M1	S-D-A (9)		
	M2	S-D-E-F (10)		
	M3	S-D-E-B (11)		
	M4	S-A-B-C (11)	Dead end (Discarded)	
	M5	S-A-B-E (12)		
6	M0	S-D-A (9)	Expand next	
	M1	S-A-D-E (10)		
	M2	S-D-E-F (10)		
	M3	S-D-E-B (11)		
	M4	S-A-B-E (12)		

7	M0	S-A-D-E (10)	Expand next	
	M1	S-D-E-F (10)		
	M2	S-D-E-B (11)		
	M3	S-A-B-E (12)		
	M4	S-D-A-B (13)		
8	M0	S-D-E-F (10)	Expand next	13
	M1	S-D-E-B (11)		17.7
	M2	S-A-B-E (12)		
	M3	S-D-A-B (13)		
	M4	S-A-D-E-F (14)		
	M5	S-A-D-E-B (15)		
9	M0	S-D-E-B (11)	Expand next	
	M1	S-A-B-E (12)		
	M2	S-D-E-F-G (13)	Destination reached (Saved)	13
	M3	S-D-A-B (13)	Path equals 13 (Discarded)	
	M4	S-A-D-E-F (14)	Path exceeds 13 (Discarded)	
	M5	S-A-D-E-B (15)	Path exceeds 13 (Discarded)	
10	M0	S-A-B-E (12)	Expand next	
	M1	S-D-E-F-G (13)	(Saved)	
	M2	S-D-E-B-A (15)	Path exceeds 13 (Discarded)	
	M3	S-D-E-B-C (15)	Path exceeds 13 (Discarded)	
11	M0	S-D-E-F-G (13)	(Saved)	
	M1	S-A-B-E-D (14)	Path exceeds 13 (Discarded)	
	M2	S-A-B-E-F (16)	Path exceeds 13 (Discarded)	

Further optimization is possible by using underestimates. Underestimates uses both path length and node distance information. Total underestimate is calculated as follows:

Underestimate = Current distance traveled + Underestimate of remaining distance

Recalculating the node distances, the following figure is obtained:

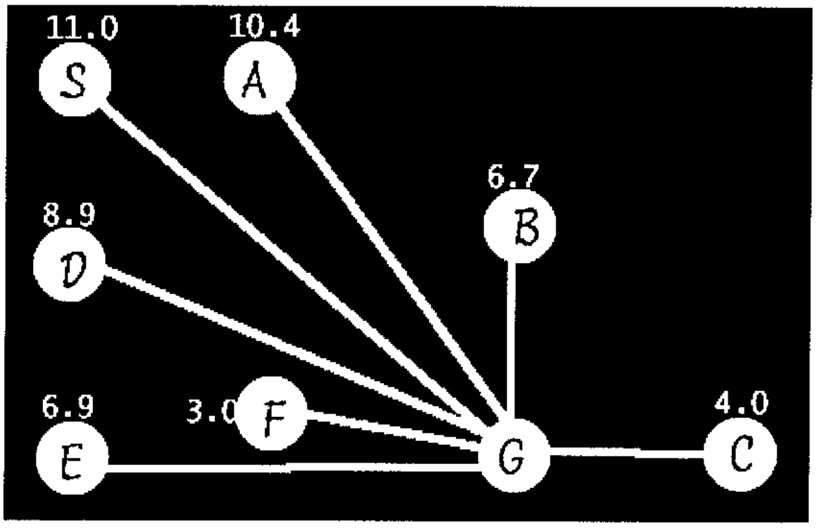


Figure 14 : Distances of Each Node to Destination [6]

The resulting steps are highlighted in the previous table. It shows a tremendous reduction of steps taken to achieve the same goal. This is the A* algorithm.

Imperfection

Sometimes imperfection is purposely introduced in the path finding to simulate a more humanlike decision rather than a rigid result. This can be done by using random nodes as restpoints or temporary destination. Or noise can be added to the distance calculations and path lengths.

CHAPTER 3
METHODOLOGY/PROJECT WORK

3.1 Procedure

The project starts with initial researches to find the most practical design from the given the wide options available. The next step is designing the mechanical and physical aspects of the robot, which are the motions and stability study. The third stage is to embed sensory devices to the robot, to complete the basic requirements of a robot. The fourth stage is to design the controller of the mobile robot. The microcontroller to be used must be studied, programmed and tested before implementing it on the final model of the robot. By then, the robot can be tested for its navigational ability, and analyzed whether modifications to its design is necessary. The final step is to introduce a higher intelligence to the navigation of the robot. The algorithm used is aimed towards achieving shortest distance (more turnings) or shortest time of travel (less turnings) to a predefined destination.

The focus of the project is to cover the first three stages and part of the fourth stage. This is to form the basics of the robot as advised by the supervisor.

The prototype built incorporates three main sensors; one in front and two by the sides. This is to ensure that the robot can maneuver without bumping into anything or sliding against the walls. The main direction which the robot follows is forward. The robot will only turn when an obstacle is detected in front of it or the wall is too close to it.

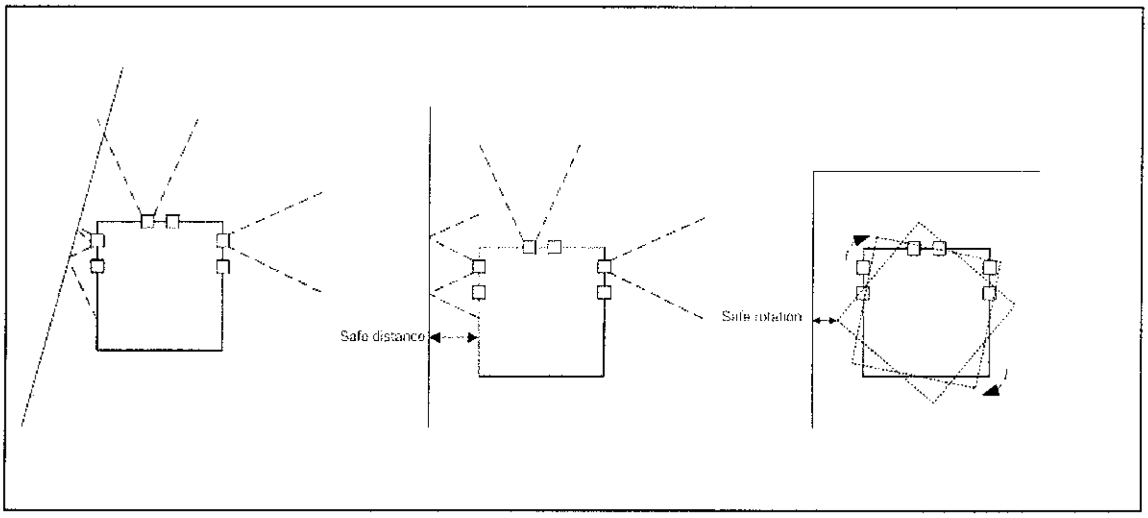


Figure 15 : Possible Obstacle Detections And Turning Methods

The ultrasonic sensors are set in such a way that it generates a ping every interval of a few hundred milliseconds. The return echo is then waited for a few more milliseconds. If within the listening period the echo did not return, the waiting period times out.

Below are possible motions of the mobile robot (Note that sensors use inversed logic):

Table 2 : Preset Sensor Inputs and Motor Rotation Direction

Sensor A (Front)	Sensor B (Right)	Sensor C (Left)	Motor 1 (Right)	Motor 2 (Left)	Direction
1	1	1	Forward	Forward	Forward
1	1	0	Stop	Forward	Turn Left
1	0	1	Forward	Stop	Turn Right
1	0	0	Reverse	Reverse	Reverse
0	1	1	Forward	Reverse	Static Turn Right
0	1	0	Reverse	Forward	Static Turn Left
0	0	1	Forward	Reverse	Static Turn Right
0	0	0	Reverse	Reverse	Reverse

The following is a flowchart of a single pinging (ping?pong!) sequence:

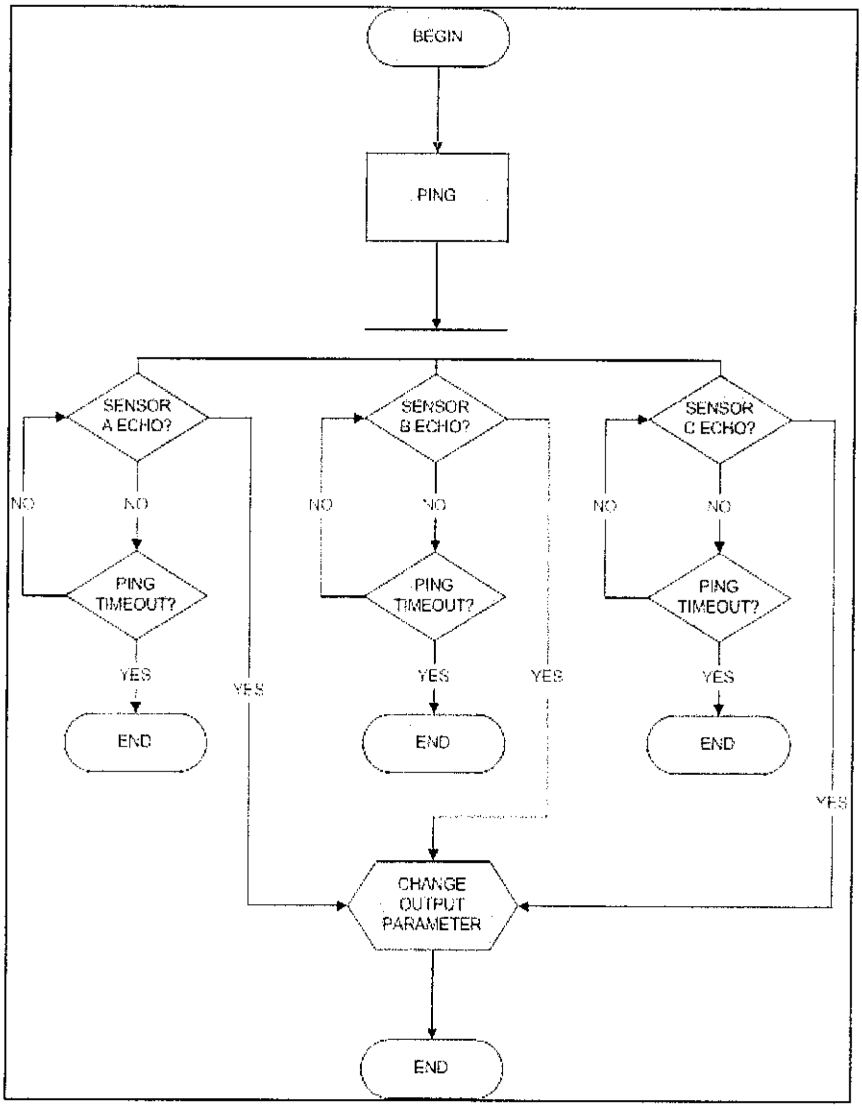


Figure 16 : Ping Sequence

3.2 Tools

Some tools which were used for the initial part of the design are:

- Software – Multisim 2001, Ultiboard 2001, MPLab 6, PIC C Compiler, WARP13 PIC Programmer
- Microcontroller – PIC16F84A
- Circuit board – Breadboards, veroboards, electronic components, ultrasonic transducers, data busses and 9-pin DB connector (Serial Port)
- Motors - 2 units 12V 60 rpm DC motors (Model : RS 336-315)

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Ultrasonic Sensor

The following test circuits were built on a solderless breadboard before implementing it on a printed circuit board:

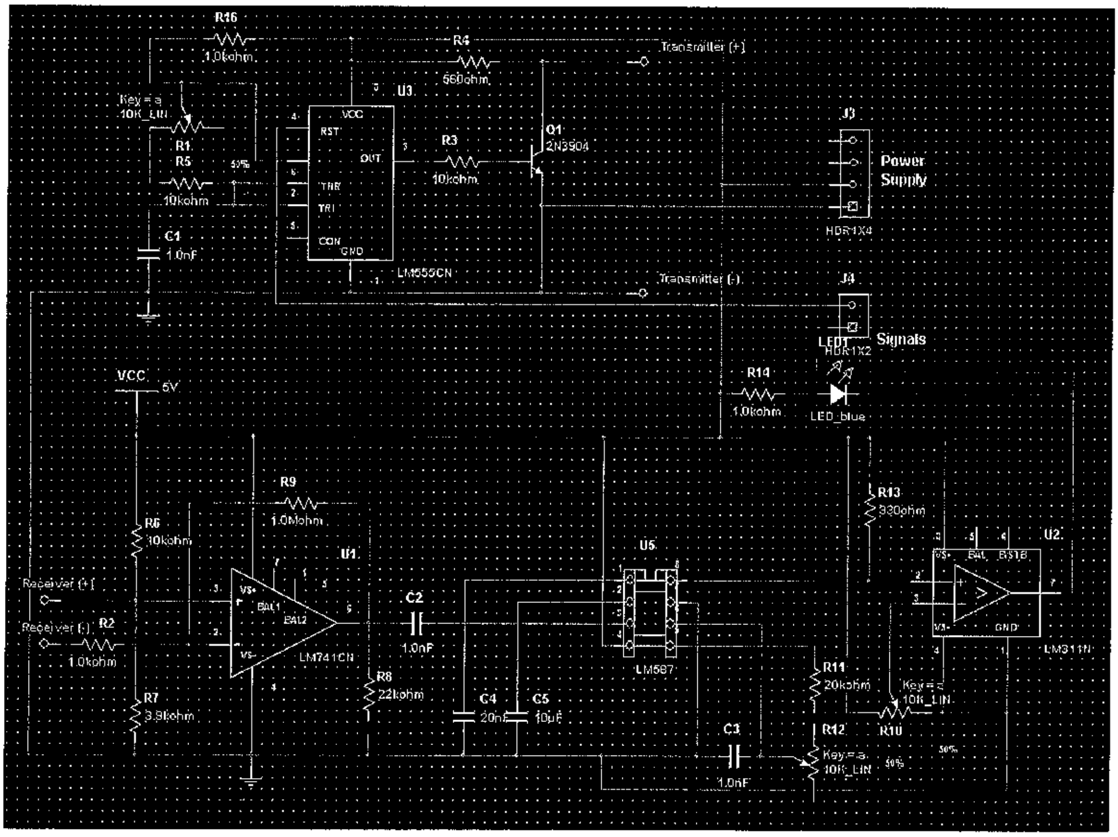


Figure 17 : Transducer Circuit

These circuits are built upon simple basic concepts. For the transmitter, the 555 timer is set to astable operation mode. The output frequency at pin 3 is determined by the following formula:

$$f = \frac{1.44}{C(R_1 + 2R_2)}$$

where R_1 is the resistance value between pin 7 to pin 8 and R_2 is the resistor value between pin 6 to pin 7.

The duty cycle is given by

$$\%\ duty\ cycle = 100\left(\frac{R_2}{R_1 + 2R_2}\right)$$

The reset pin (pin 4), when set to high, will cause the 555 timer to run. When set to low, the timer will reset and stop transmitting pulses. In this circuit, the reset pin is held high for testing purposes.

The receiver side is made of 3 main sections, namely an operational amplifier, a tone decoder and a comparator. The operational amplifier amplifies the incoming signal received by the ultrasonic receiver by the following factor

$$Gain = \frac{R_{feedback}}{R_{input}}$$

The 2^{nd} section, the tone decoder acts as a filter, where it detects only a preset tone (frequency). The detection frequency can be adjusted using the following formula

$$f_o \cong \frac{1}{1.1\ R_1 C_1}$$

where R_1 is the resistance between pin 5 and pin 6 and C_1 is the capacitance at pin 6. The relationship graph between capacitance, resistance and frequency is given as follows

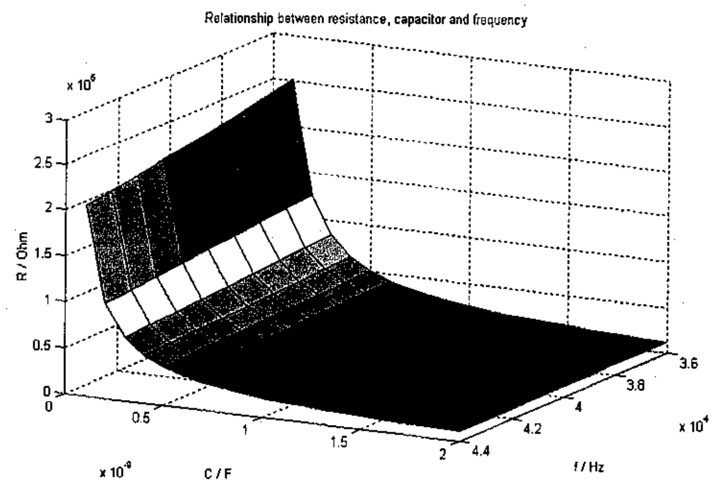


Figure 18 : Relationship Between Resistance, Capacitance And Frequency For LM567 Tone Decoder

The last section (LM311) is a comparator used to minimize false triggering. The triggering level can be set by adjusting the resistance at pin 3.

The output at the amplifier stage was not quite smooth, and caused the LM567 output to blink, but still show fairly correct results. This is a sample waveform obtained at the output of the operational amplifier in the receiver circuit when a signal is present:

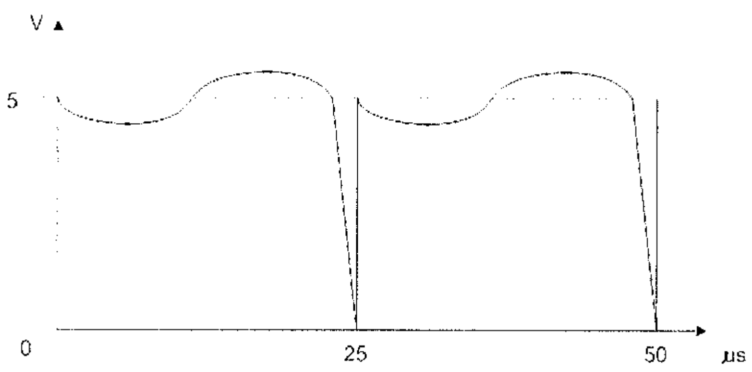
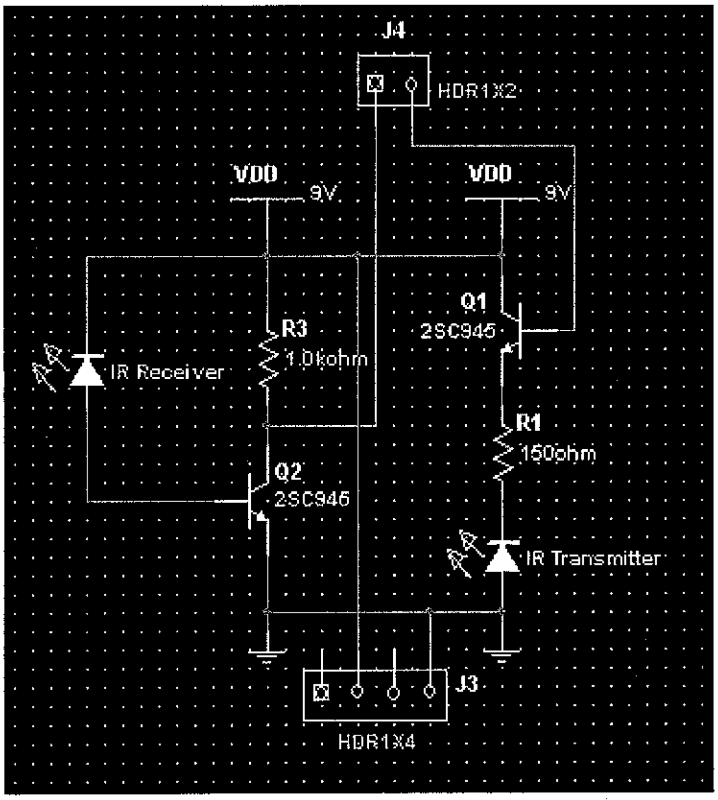


Figure 19 : Graph of Voltage vs Time

The cause has been identified as the internal oscillation of the operational amplifier IC. The effect of the spikes can be reduced by careful filtering via the settings of the LM567 tone decoder.

4.2 Infrared Transceiver Circuit



The infrared transceiver circuit is an interchangeable part for the ultrasonic transducer, used as an alternative detection method. The IR transmitter (right half) is controlled by the current supplied into the base of Q1. The IR receiver on the other hand controls the current going into the base of Q2. When the IR receiver detects a signal, it quickly allows some current to pass through and saturate the base of Q2. This causes a direct connection from the collector to the emitter and hence to the ground. By taking the voltage at the collector, the output is given as a HIGH when no signal is received and a LOW when signal is present, thus operating in inverse logic mode, similar to the ultrasonic sensors.

4.3 Motor Control

The motors used in this project are RS336-315 12V 60rpm dc motors. The following H-Bridge circuit is used to control the forward/reverse rotation of the motors:

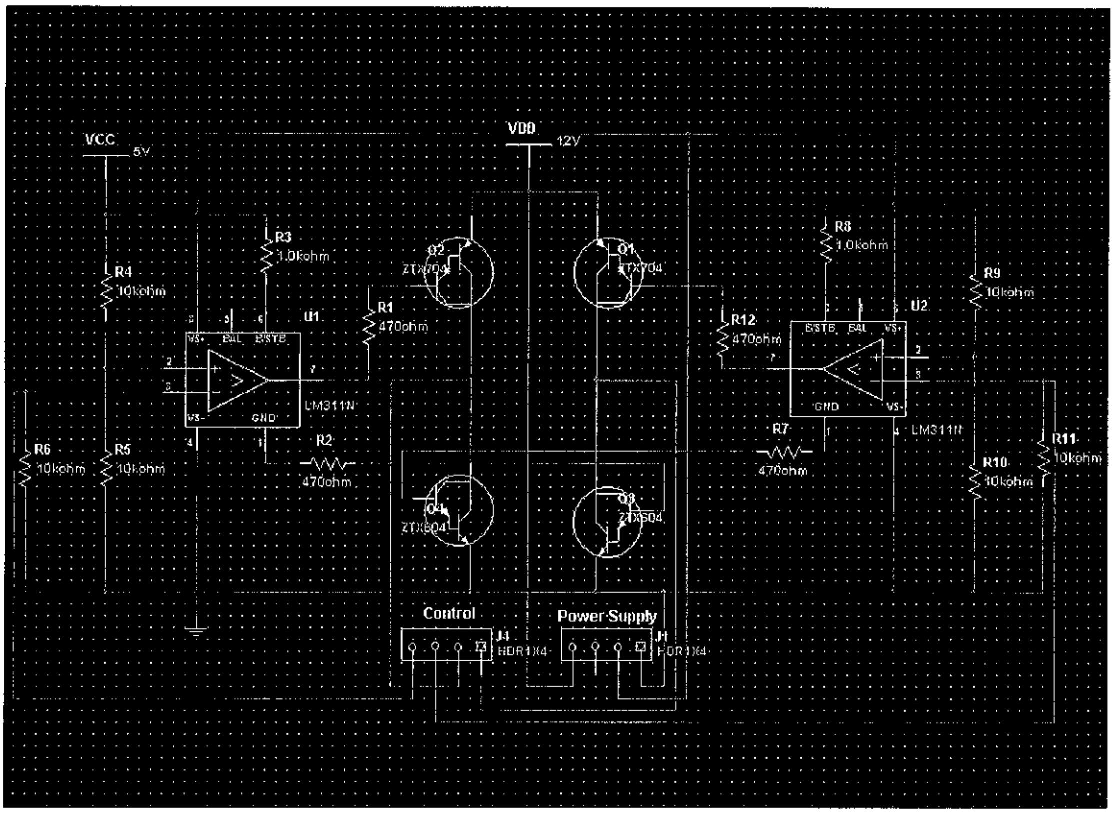


Figure 20 : H-Bridge Circuit

The actual transistors used are TIP32C (for Q1 & Q2) and TIP31C (for Q3 & Q4) as opposed to the ones shown in the figure. The actual transistors are not presented in the schematics because the specific components are unavailable in the Multisim 2001 parts library. Inputs 1 and 2 of J4 will determine the direction of rotation of the motor, and is controlled using a microcontroller. When either input is set to high, the motor will rotate in a certain direction. The comparator is used to minimize false triggering at the inputs of the transistors.

4.4 Mechanical Construction

The body is made of plastic tray with motors and circuitry attached inside and wheels attached outside.

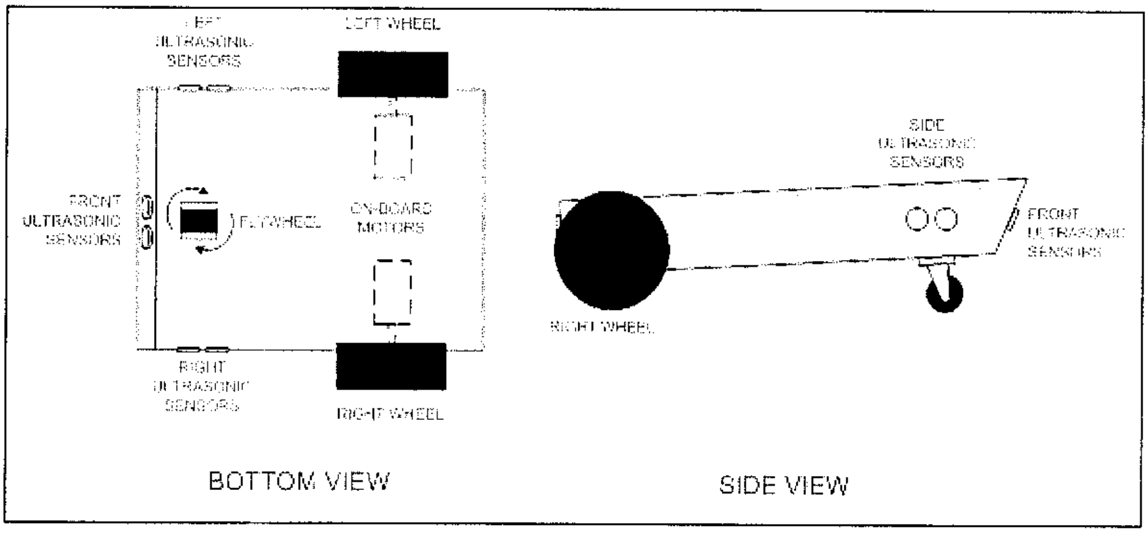


Figure 21 : Mechanical Construction of the Robot

4.5 Microcontroller

The microcontroller PIC16F84 is used primarily as a logic and sequential controller for navigation. The PIC16F84 has 13 I/O (5 on Port A and 8 on Port B). The oscillator used is of crystal type with fixed oscillation frequency of 4 Mhz, producing an instruction cycle speed of 2MHz. However, due to a two-stage pipelining architecture, the average throughput is almost 4MIPS. The high speed is necessary to calculate the propagation of ultrasonic waves. The selection of this microcontroller is based on its ease of programming for future developments.

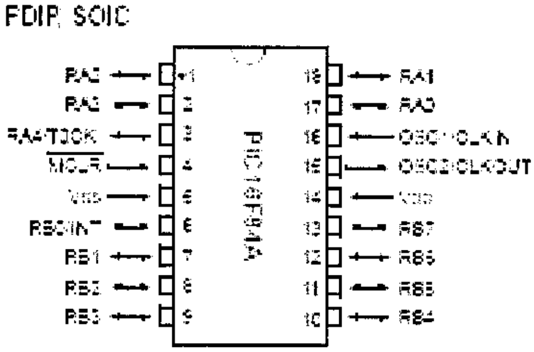


Figure 22 : PIC16F84 Pin Layout [7]

The microcontroller board is built as follows:

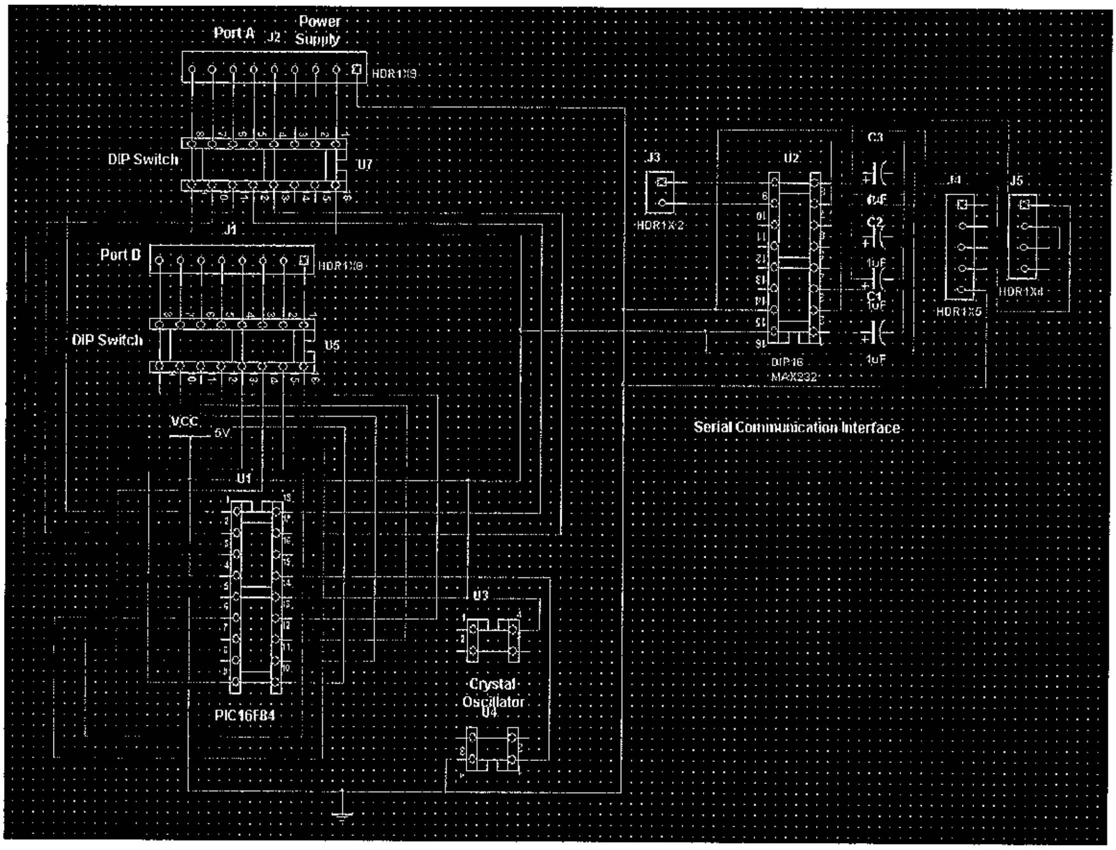


Figure 23 : Microcontroller Board

The microcontroller board is equipped (although not used) with a serial communication interface to enable expansion and interaction with a computer's serial port. All I/O ports are connected to DIP switches to manually enable or disable the desired ports.

Microcontroller programming is done in assembly rather than C as previous attempts with C resulted in insufficient memory problems. Two basic types of programs has been produced, the first is the basic collision avoidance logic program and the second a smarter path correction program.

The first program moves the robot in forward direction. Upon detection of obstacles, it turns accordingly. The logical motions are provided in Table 2. A tweak however has been made to this program in the final edition to eliminate the infinite loop of forward-reverse when the robot moves between narrowing walls. This is done by sequencing the reverse motion with a static left turn motion, hence moving the program into a different logic state.

The second program is aimed at path correction. The robot tries to move in a forward direction. If obstructed, it turns left or right and moves on. The robot then tries to resume its original direction with proper right-left turnings. The trick to this program is to allocate two variables, namely the direction and the X position. These two, together with sensor inputs, will decide whether the robot should turn or move on. Also, possibility of going in circles have been eliminated by tracking the number of turns made. However, this program has not been tested thoroughly as it is still a new addition at the time of compilation of this report. The following diagram shows the intended motion of the robot for this program:

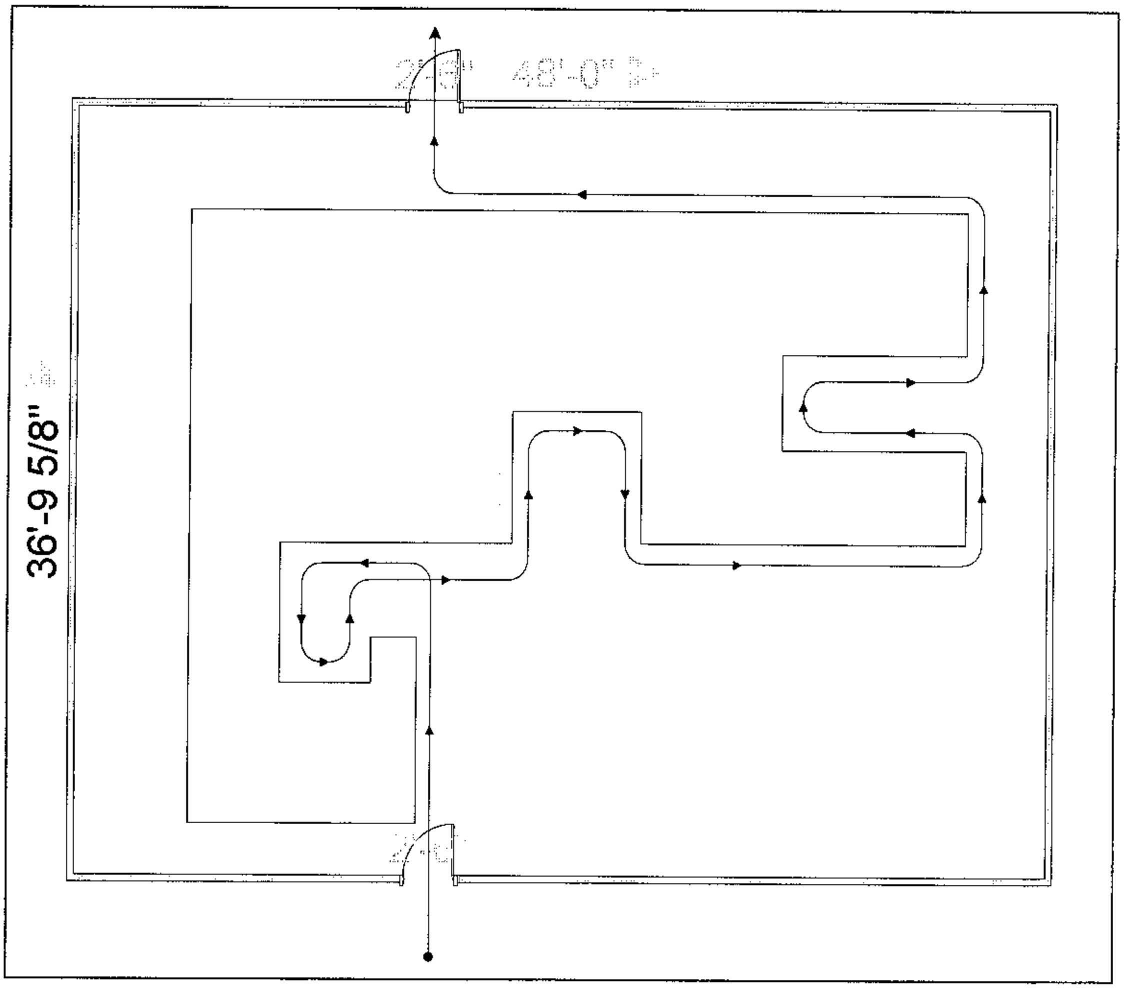


Figure 24 : Robot Maneuvering Around Obstacles Using the 2nd Program

About The Program

The program is controlled by sensors and three variables, namely direction (DIR), right-left turn (RTLT) and x-displacement (X). DIR and RTLT are basically the same except that DIR limits its values to 0x01 – 0x04 while RTLT allows value ranges of 0x01 – 0x06 (This separation is done to simplify programming). To avoid confusion and aid understanding, RTLT will be represented as DIR hereon. The directions (DIR) are named North (N), South (S), West (W) and East (E).

Consider the previous diagram (Figure 24). Assume we start the robot at point A which is just outside the entrance. Point A is set as the 0 axis of x-displacement, having a biased value of 0x10. The robot is heading North, represented in DIR as 0x04. When no obstacle is detected in front of the robot, it moves forward. Upon detection of an obstacle in front and no obstacle to the left, it turns left. Variable DIR is now subtracted by 1 and becomes 0x03 which represents West. The robot then strolls along the wall for, say, 2 periods of time. X now has been subtracted with 2 for the 2 periods of time. Another wall soon is detected, and the robot has to turn left. 1 is subtracted from DIR, becoming 0x02 representing South. Assume the robot moves another 2 periods of time towards South. Meanwhile the robot always monitors its right being the next default turn. No changes to any of the two variables occur.

The robot then sees another obstacle in front and turns left instead of the default right. DIR is subtracted. It moves 1 unit of time forward and X is incremented. Another wall is seen and the robot turns left, heading north again.

Now, having turned in circular motion, the robot then tries a right turn. The logic follows similarly as the previous motions. The following table summarizes the changes in the variables, direction and motion of the robot:

Table 3 : Changes in Variables While Running Program Navigator 2.5 for Map in Figure 24

Steps	X	DIR	Sensors			Motion
			L	F	R	
1.	0x10	N (0x04)	0	0	0	Forward
⋮	⋮	⋮	⋮	⋮	⋮	⋮
5.	0x10	N (0x04)	0	1	0	Left
6.	0x10	W (0x03)	0	0	1	Forward
7.	0x0F	W (0x03)	0	0	1	Forward
8.	0x0E	W (0x03)	0	1	1	Left
9.	0x0E	S (0x02)	0	0	1	Forward
10.	0x0E	S (0x02)	0	0	1	Forward
11.	0x0E	S (0x02)	0	1	1	Left
12.	0x0E	E (0x01)	0	0	1	Forward
13.	0x0F	E (0x01)	0	1	1	Left
14	0x0F	N (0x04)	0	0	1	Forward
15.	0x0F	N (0x04)	0	0	1	Forward
16.	0x0F	N (0x04)	0	1	0	Right
17.	0x0F	E (0x01)	1	0	0	Forward
18.	0x10	E (0x01)	1	0	0	Forward
⋮	⋮	⋮	⋮	⋮	⋮	⋮
22.	0x14	E (0x01)	0	0	0	Left
23.	0x14	N (0x04)	1	0	0	Forward
24.	0x14	N (0x04)	1	0	0	Forward
25.	0x14	N (0x04)	1	1	0	Right
26.	0x15	E (0x01)	1	0	0	Forward
27.	0x15	E (0x01)	1	1	0	Right
28.	0x15	S (0x06)	1	0	0	Forward
29.	0x15	S (0x06)	1	0	0	Forward
30.	0x15	S (0x06)	0	0	0	Left
31.	0x15	E (0x01)	1	0	0	Forward
⋮	⋮	⋮	⋮	⋮	⋮	⋮
38.	0x1C	E (0x01)	0	0	0	Left
39.	0x1C	N (0x04)	1	0	0	Forward
40.	0x1C	N (0x04)	1	0	0	Forward
41.	0x1C	N (0x04)	0	0	0	Left
42.	0x1C	W (0x03)	1	0	0	Forward

Steps	X	DIR	Sensors			Motion
			L	F	R	
⋮	⋮	⋮	⋮	⋮	⋮	⋮
44.	0x1A	W (0x03)	1	1	0	Right
45.	0x1A	N (0x04)	1	0	0	Forward
46.	0x1A	N (0x04)	1	1	0	Right
47.	0x1A	E (0x01)	1	0	0	Forward
⋮	⋮	⋮	⋮	⋮	⋮	⋮
49.	0x1C	E (0x01)	1	0	0	Forward
50.	0x1C	E (0x01)	0	0	0	Left
51.	0x1C	N (0x04)	1	0	0	Forward
⋮	⋮	⋮	⋮	⋮	⋮	⋮
53.	0x1C	N (0x04)	0	0	0	Left
54.	0x1C	W (0x03)	1	0	0	Forward
⋮	⋮	⋮	⋮	⋮	⋮	⋮
61.	0x10	W (0x03)	1	0	0	Right
62 onwards	0x10	N (0x04)	0	0	0	Forward

Notice the difference in DIR value for South. This determines whether the robot should turn right or left when heading South to avoid going in loops.

The programs are attached in APPENDIX A for reference.

4.6 Regulated Power Supply

The power supply is built as follows:

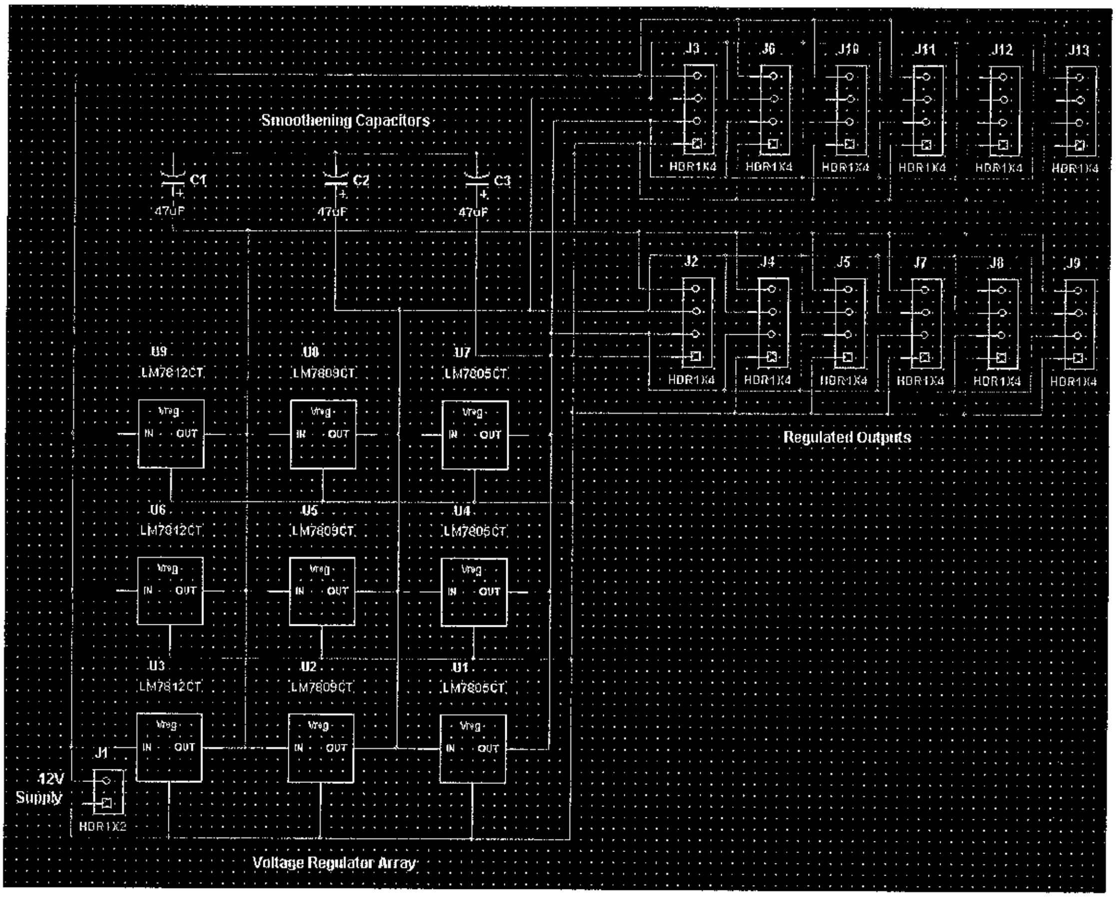


Figure 25 : Regulated Power Supply

The J1 connector takes an input of 12V supply from a power source; in this case, 2 sealed valve-regulated 6V lead-acid batteries with rated 4.5AH connected in series. A 1 + 2 redundancy (300%) is optionally prepared in the Voltage Regulator Array. The redundancy provides two main benefits:

- Higher reliability – In case of a failure of one component, two others will still be able to provide the necessary regulation.
- Higher operating current – Each of the components has a rating of about 1A maximum current (depending on the heatsink). By having the 1 + 2 architecture, the maximum current can be increased up to 3A when necessary. It is to be noted however, that the first regulators (LM7812) will limit the current to 3A for subsequent circuits and regulators. This means that LM7809 and LM7805 will actually be providing much less current.

The Regulated Output consists of two rows of connector sets. The lower sets provide regulated 12V, 9V and 5V supply, while the upper sets provide unregulated 12V supply. This is especially useful when high current 12V supply is needed, such as driving the motors, so as not to drain the current otherwise may be used by the 9V and 5V supply.

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The outcome of this project is a prototype of bare minimum which will perform as the basis for further enhancements. Although the prototype seems to be a relatively simple one, but the process of coming up with it is tedious and tricky. Eventhough most of the circuitry is taken elsewhere, the circuits did not function as they should when the actual prototype is built, thus a painstaking troubleshooting work had to be performed. As one may have experienced, troubleshooting is one of the most difficult part in a design.

The project has successfully achieved its goals for this year. The author has successfully come up with a basic prototype which will serve as the basis for future developments.

In the process, the author has gained invaluable knowledge in fields which the author has never learnt before. In addition, the author has experienced problems and has tackled them successfully especially in the design and testing of the ultrasonic sensors which took months to resolve. The constraint of time forced the author to organize work and resources more carefully. The author is now also more appreciative of the works done by other robotic engineers around the world which he has studied and which has amazed the author by their incomparable creativity and knowledge.

5.2 Recommendation

With the basic building blocks being laid for, the next step to do is to improve on the current design. The mechanical aspects of the prototype are somewhat very crude. In terms of electronic circuitry, an ultrasonic transmitter-receiver circuit can be designed to utilize only one transducer instead of two separate transducers. A lighter and more compact power supply may be used to replace the existing one.

Perhaps the most important improvement can be made is in terms of PIC16F84 programming, where intelligence can be applied for the navigation control. The biggest challenge of doing this is the limited amount of memory available on this PIC, thus forcing the programmer to use assembly language instead of C in most times. Other improvement which can be made is to set up a Visual Basic program as a GUI for communications with the PIC16F84 in order to retrieve the map of the terrain and to set the goal or destination of the mobile robot. Further, a wireless communication can be implemented so that the PIC16F84 can transmit real-time data and the controller can manipulate interactively.

As presented in the theory section, the author regrets not having the opportunity to complete the programming for A* algorithm path finding due to time constraints. Specifically in path planning, a construction of Voronoi diagram can be implemented in the PIC16F84 by allowing the robot to run in an environment assessment routine. With the map stored in the robot, the robot can then be run in a self localization mode, and then the algorithm can be tested whether it is effective in finding its way to the target goal or destination. This can be helpful if one were to evolve the model to be used as maze mouse.

At a much more advanced level, digital imaging may be performed to study the surroundings and perhaps fed to the processor to study the terrain, instead of relying solely on ultrasonic sensors. At this time, most probably a different processor should be used instead of a microcontroller, or a wireless RF communications interface can move the processing burden onto a remote computer and using the microcontroller mainly as a slave to gather data and execute commands.

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APPENDIX A

PIC16F84 SOURCE CODES IN ASSEMBLY

```
;-----------------------------------------------------------
;       Final Year Project
;       Student Name    : Abu Masnur Abu Kassim
;       Student ID      : E0716
;       Topic           : Mobile Robot
;       Version         : 1.5
;       Program Name    : Navigator
;       Description     : This program avoids collisions with
;                         obstacles in its path.
;-----------------------------------------------------------

        LIST            P=PIC16F84
        #INCLUDE        <P16F84.INC>

;--------------------- DEFINITIONS -------------------------

TEMP            equ     0x10    ; Buffer to define output signals
COUNTER1        equ     0x12
COUNTER2        equ     0x13
COUNTER3        equ     0x14

        org             0x00

;-----------------------------------------------------------

INITIALIZE
        clrf    PORTB           ; Clear all Port B data latches
        bsf     STATUS, RP0     ; Switch to Bank 1
        movlw   b'00011111'     ; RA<4:0> set as inputs
        movwf   TRISA
        clrf    TRISB           ; Set all Port B as outputs

        bcf     STATUS, RP0     ; Switch to Bank 0
        clrf    PORTB           ; Clear all Port B data latches
        clrf    TMR0
        clrwdt
        clrf    INTCON

;-----------------------------------------------------------

START
        movlw   b'00000111'
        iorwf   PORTB           ; Start ping
        call    DELAY
        bcf     STATUS, 2       ; Clear zero bit
        clrf    TEMP            ; Clear TEMP buffer
        clrwdt
        movlw   0x80
        movwf   COUNTER1
;-----------------------------------------------------------

ECHORETURN

        btfss   PORTA, 2        ; L Sensor Received Echo?
        bsf     TEMP, 2         ; Yes. Set bit 2 to 1
        btfss   PORTA, 1        ; F Sensor Received Echo?
        bsf     TEMP, 1         ; Yes. Set bit 1 to 1
        btfss   PORTA, 0        ; R Sensor Received Echo?
        bsf     TEMP, 0         ; Yes. Set bit 0 to 1
        decfsz  COUNTER1
        goto    ECHORETURN

;-----------------------------------------------------------

MOTION0
        bcf     STATUS, 2       ; Clear zero bit
        movf    TEMP, F         ; Test for condition 000
        btfss   STATUS, 2
        goto    MOTION1
        movlw   b'10100111'     ; R=Fwd, L=Fwd
        movwf   PORTB
        goto    START

;-----------------------------------------------------------

MOTION1
        bcf     STATUS, 2       ; Clear zero bit
        movlw   b'00000001'     ; Test for condition 001
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    MOTION2
        movlw   b'00100111'     ; L=Stop, R=Fwd
        movwf   PORTB
        goto    START

;-----------------------------------------------------------

MOTION2
        bcf     STATUS, 2       ; Clear zero bit
        movlw   b'00000010'     ; Test for condition 010
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    MOTION3
        movlw   b'01100111'     ; L=Rev, R=Fwd
        movwf   PORTB
        call    DELAY
        call    DELAY
        goto    START
```

```
;----------------------------------------------------------------

MOTION3
        bcf     STATUS, 2       ; Clear zero bit
        movlw   b'00000011'     ; Test for condition 011
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    MOTION4
        movlw   b'01100111'     ; L=Rev, R=Fwd
        movwf   PORTB
        call    DELAY
        call    DELAY
        goto    START

;----------------------------------------------------------------

MOTION4
        bcf     STATUS, 2               ; Clear zero bit
        movlw   b'00000100'             ; Test for condition 100
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    MOTION5
        movlw   b'10000111'             ; L=Fwd, R=Stop
        movwf   PORTB
        goto    START

;----------------------------------------------------------------

MOTION5
        bcf     STATUS, 2       ; Clear zero bit
        movlw   b'00000101'     ; Test for condition 101
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    MOTION6
        movlw   b'01100111'     ; L=Rev, R=Fwd
        movwf   PORTB
        goto    START

;----------------------------------------------------------------

MOTION6
        bcf     STATUS, 2       ; Clear zero bit
        movlw   b'00000110'     ; Test for condition 110
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    MOTION7
        movlw   b'10010111'     ; L=Fwd, R=Rev
        movwf   PORTB
        call    DELAY
        call    DELAY
        goto    START

;----------------------------------------------------------------

MOTION7
        bcf     STATUS, 2       ; Clear zero bit
        movlw   b'00000111'     ; Test for condition 111
        subwf   TEMP, W
        btfss   STATUS, 2
        goto    START
        movlw   b'01100111'     ; L=Rev, R=Fwd
        movwf   PORTB
        call    DELAY
        call    DELAY
        goto    START

;--------------------- DELAY subroutine ---------------------

; The DELAY subroutine is used to delay the execution of the
; next command by a specific period as determined by the
; values of COUNTER1, COUNTER2 and COUNTER3

DELAY
        clrwdt
        movlw   0xC8            ; Set COUNTER1
        movwf   COUNTER1        ; to decimal 200

DELAY1
        movlw   0xC8            ; Set COUNTER2
        movwf   COUNTER2        ; to decimal 200

DELAY2
        movlw   0x02            ; Set COUNTER3
        movwf   COUNTER3        ; to decimal 2

DELAY3
        decfsz  COUNTER3, 1
        goto    DELAY3
        decfsz  COUNTER2, 1
        goto    DELAY2
        decfsz  COUNTER1, 1
        goto    DELAY1
        return
        end
```

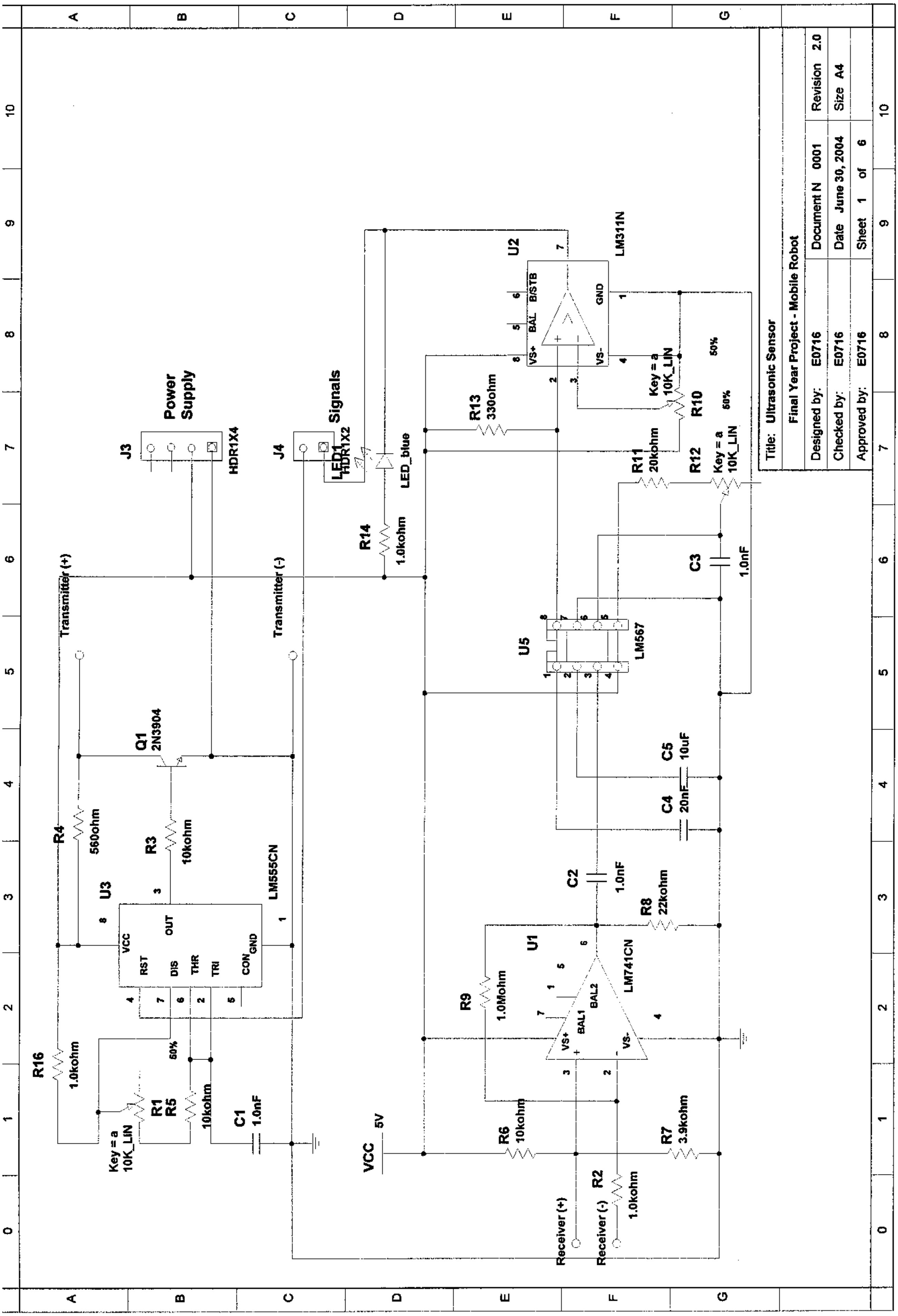
```
;-------------------------------------------------------------
;
;       Final Year Project
;       Student Name    : Abu Masnur Abu Kassim
;       Student ID      : E0716
;       Topic           : Mobile Robot
;       Version         : 2.16
;       Program Name    : Navigator 2
;       Description     : This program attempts to return to its
;                         original path as it avoids obstacles.
;
;-------------------------------------------------------------

        LIST            P=PIC16F84
        #INCLUDE        <P16F84.INC>

;-------------------------------------------------------------
;       DEFINITIONS
;-------------------------------------------------------------

TEMP            equ     0x10    ; <2:0> Sensor signal buffer
DIR             equ     0x11    ; <1:0> Direction buffer
X               equ     0x12    ; <7:0> X displacement buffer
RTLT            equ     0x13    ; <3:0> LT-RT counter

COUNTER1        equ     0x14    ; Delay counter 1
COUNTER2        equ     0x15    ; Delay counter 2
COUNTER3        equ     0x16    ; Delay counter 3

        org             0x05

;-------------------------------------------------------------
INITIALIZE
;-------------------------------------------------------------

        clrf    PORTB           ; Clear all Port B data latches
        bsf     STATUS, RP0     ; Switch to Bank 1
        movlw   b'00011111'     ; RA<4:0> set as inputs
        movwf   TRISA
        clrf    TRISB           ; Set all Port B as outputs

        bcf     STATUS, RP0     ; Switch to Bank 0
        clrf    PORTB           ; Clear all Port B data latches
        clrf    TMR0
        clrwdt
        clrf    INTCON
        movlw   b'00000100'     ; Set up RTLT
        movwf   RTLT
        movlw   b'00000100'     ; Set up DIR
        movwf   DIR
        movlw   b'00010000'     ; Set up X
        movwf   X
        call    DELAY
        call    DELAY

;-------------------------------------------------------------
START
;-------------------------------------------------------------

        call    DELAY
        movlw   b'00000111'     ; Start ping
        movwf   PORTB
        call    DELAY

        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000101'     ; Test if DIR reached 101
        subwf   DIR, 0
        btfss   STATUS, 2
        goto    A               ; No
        movlw   b'00000100'     ; Yes
        subwf   DIR, 1
        goto    ECHORETURN

A       movlw   b'11111000'
        andwf   STATUS, 1
        movf    DIR, 1          ; Test if DIR reached 0
        btfss   STATUS, 2
        goto    ECHORETURN      ; No
        movlw   b'00000100'     ; Yes
        addwf   DIR, 1

;-------------------------------------------------------------
ECHORETURN
;-------------------------------------------------------------

        clrwdt
        movlw   0xF0
        movwf   COUNTER1
        clrf    TEMP

ECHORETURN1
        btfss   PORTA, 2        ; L Sensor Received Echo?
        bsf     TEMP, 2         ; Yes. Set bit 2 to 1
        btfss   PORTA, 1        ; F Sensor Received Echo?
        bsf     TEMP, 1         ; Yes. Set bit 1 to 1
        btfss   PORTA, 0        ; R Sensor Received Echo?
        bsf     TEMP, 0         ; Yes. Set bit 0 to 1
        decfsz  COUNTER1
        goto    ECHORETURN1
```

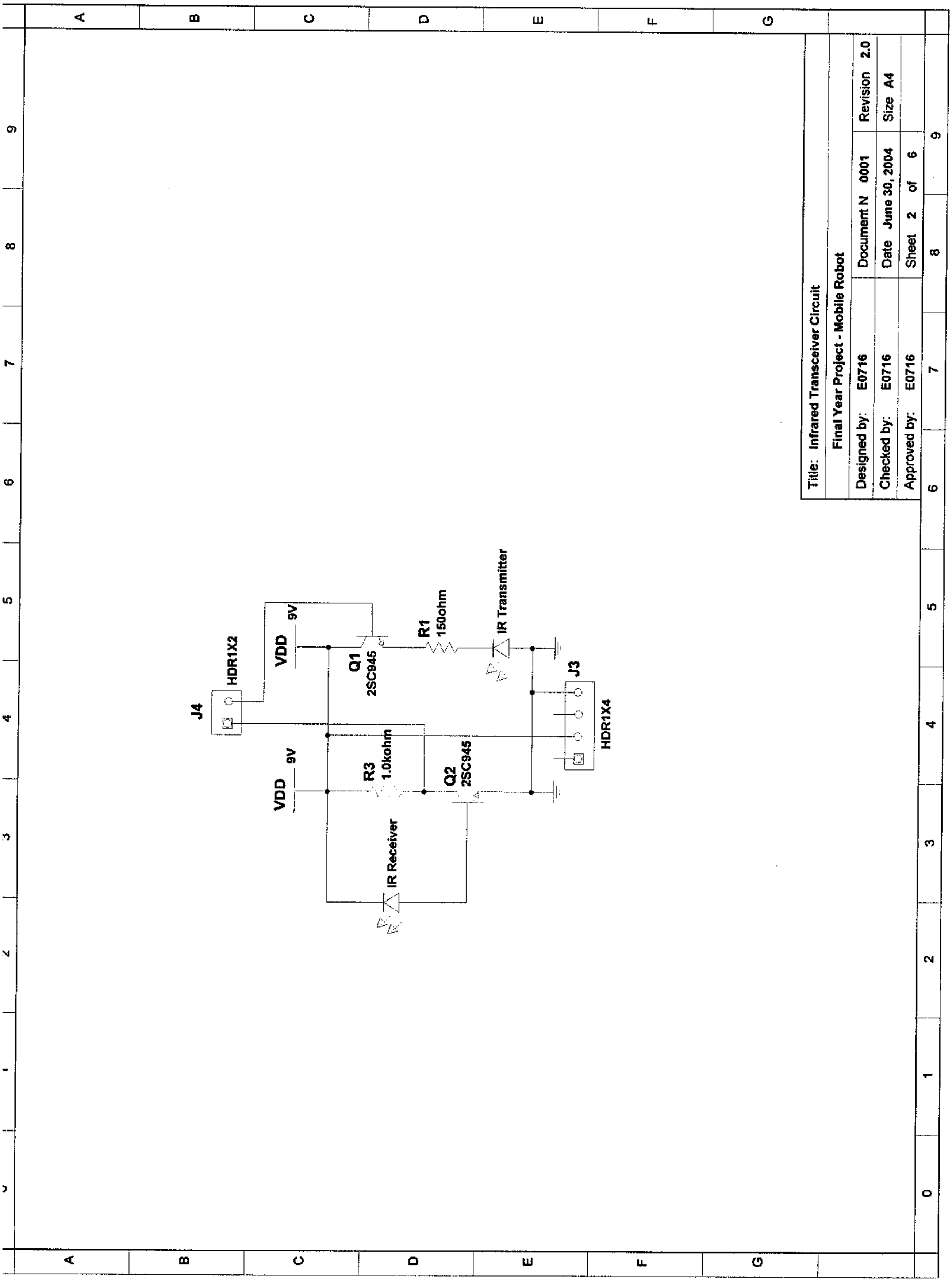
```
;------------------------------------------------------------
CONDITION
;------------------------------------------------------------

        clrwdt
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00010000'
        subwf   X, 0
        btfss   STATUS, 2
        goto    CORRECTION       ; X != 0

CONDITION1                       ; X = 0
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000100'
        subwf   DIR, 0
        btfss   STATUS, 2
        goto    CORRECTION       ; DIR != N

CONDITION2                       ; DIR = N
        btfss   TEMP, 1
        goto    NORMAL           ; Sensor F = 0
        goto    BLOCKED          ; Sensor F = 1

;------------------------------------------------------------
NORMAL
;------------------------------------------------------------

        call    FORWARD
        goto    START

;------------------------------------------------------------
BLOCKED
;------------------------------------------------------------

        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000011'      ; Test for condition 011
        subwf   TEMP, 0
        btfss   STATUS, 2
        goto    BLOCKED1         ; False
        call    LEFT             ; True
        goto    START

BLOCKED1
        btfss   TEMP, 2          ; Test for condition 11x
        goto    BLOCKED2         ; False
        call    RIGHT            ; True
        goto    START

BLOCKED2
        movlw   b'11111000'
        andwf   STATUS, 1
        movf    RTLT, 1          ; Test for condition 011, RTLT = 0?
        btfss   STATUS, 2
        goto    BLOCKED3
        call    RIGHT            ; RTLT = 0
        goto    START

BLOCKED3
        call    LEFT             ; RTLT > 0
        goto    START

;------------------------------------------------------------
CORRECTION
;------------------------------------------------------------

        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000011'
        subwf   DIR, 0
        btfsc   STATUS,2         ; Direction West?
        goto    WEST             ; Yes (DIR = W)

        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000001'
        subwf   DIR, 0
        btfsc   STATUS, 2        ; Direction East?
        goto    EAST             ; Yes (DIR = E)

        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000010'
        subwf   DIR, 0
        btfsc   STATUS, 2        ; Direction South?
        goto    SOUTH            ; Yes (DIR = S)
        goto    NORTH            ; No (DIR = N)

;------------------------------------------------------------

WEST
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00010000'
        subwf   X, 0
        btfss   STATUS, 0        ; Test if X >= 0
        goto    WEST1            ; No
        btfss   STATUS, 2        ; Yes. Test if X = 0
        goto    WEST2            ; No
```

```
WEST1                           ; X <= 0
        btfsc   TEMP, 0         ; Yes. Test if condition (xx1)
        goto    WEST2           ; Yes
        call    RIGHT           ; No (xx0)
        call    DELAY
        clrf    PORTB
        call    DELAY
        call    FORWARD
        goto    START

WEST2                           ; X > 0
        btfsc   TEMP, 1         ; Test for condition (x1x)
        goto    BLOCKED         ; Yes (x1x)
        decf    X, 1            ; No (x0x)
        call    FORWARD
        goto    START

;-----------------------------------------------------------------

EAST
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00010000'
        subwf   X, 0
        btfss   STATUS, 0       ; Test if X >= 0
        goto    EAST2           ; No (X < 0)


EAST1                           ; X >=0
        btfsc   TEMP, 2         ; Yes. Test if condition (1xx)
        goto    EAST2           ; Yes
        call    LEFT            ; No (0xx)
        call    DELAY
        clrf    PORTB
        call    DELAY
        call    FORWARD
        goto    START

EAST2                           ; X < 0
        btfsc   TEMP, 1         ; Test for condition (x1x)
        goto    BLOCKED         ; Yes (x1x)
        incf    X, 1            ; No (x0x)
        call    FORWARD
        goto    START

;-----------------------------------------------------------------

SOUTH
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000010'
        xorwf   RTLT, 0
        btfss   STATUS, 2
        goto    SOUTH2

        btfsc   TEMP, 0         ; (xx0)
        goto    SOUTH1          ; (xx1)
        call    RIGHT           ; (xx0)
        goto    START

SOUTH1
        btfss   TEMP, 1
        call    FORWARD
        btfsc   TEMP, 1
        call    LEFT
        goto    START

SOUTH2
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00000110'
        xorwf   RTLT, 0
        btfss   STATUS, 2
        goto    NORMAL

        btfsc   TEMP, 2
        goto    SOUTH3          ; (1xx)
        call    LEFT            ; (0xx)
        call    DELAY
        clrf    PORTB
        call    DELAY
        call    FORWARD
        incf    X
        goto    START

SOUTH3                          ; (1xx)
        btfss   TEMP, 1
        call    FORWARD         ; (10x)
        btfsc   TEMP, 1
        call    RIGHT           ; (11x)
        goto    START

;-----------------------------------------------------------------

NORTH
```

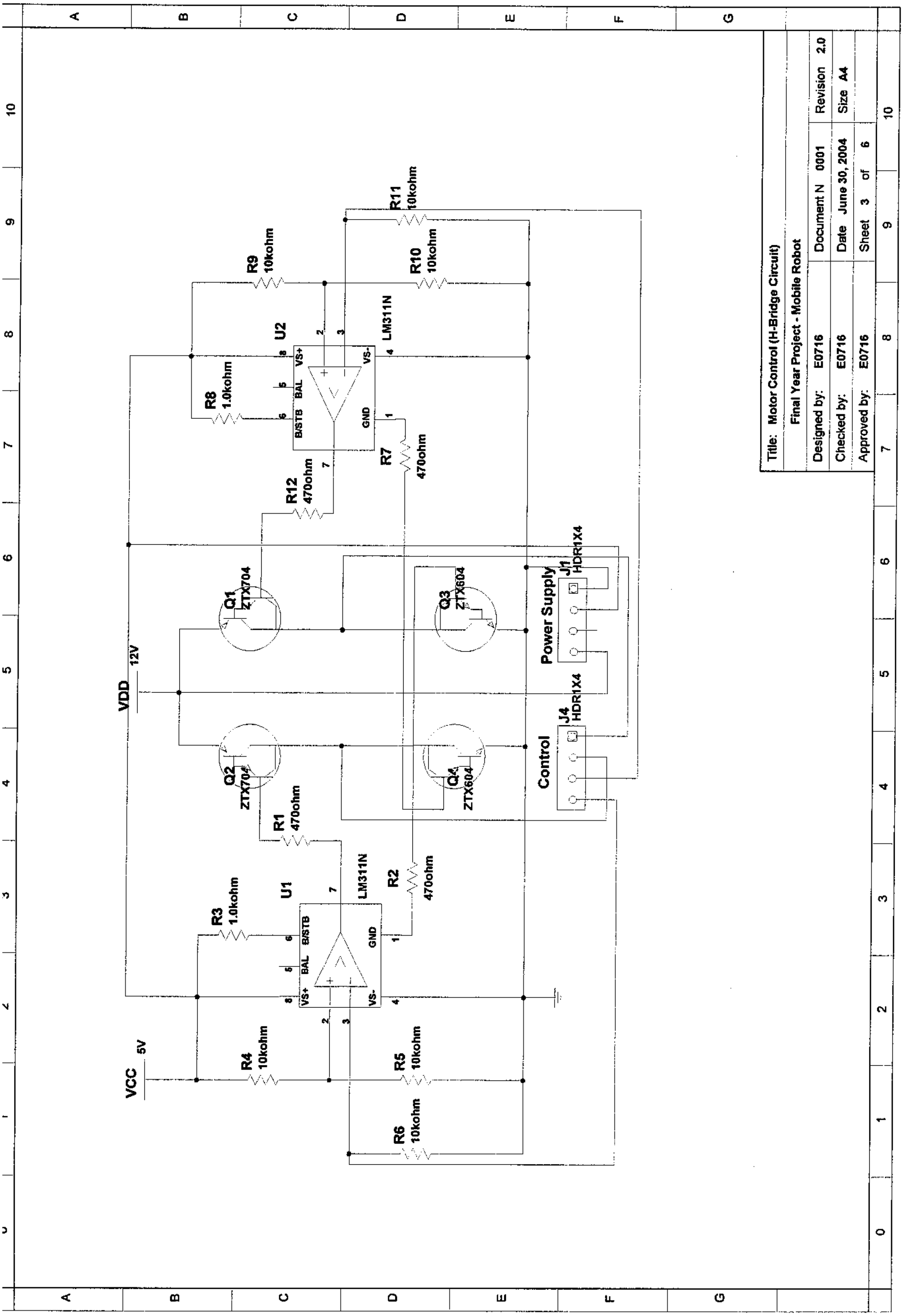
```
        movlw   b'11111000'
        andwf   STATUS, 1
        movlw   b'00010000'
        subwf   X, 0
        btfss   STATUS, 0       ; Test if X >= 0
        goto    NORTH1          ; No (X < 0)
        btfss   STATUS, 2       ; Yes. Test if X = 0
        goto    NORTH2          ; No (X > 0)

NORTH1                          ; X <= 0
        btfsc   TEMP, 0
        goto    NORTH3          ; (xx1)
        call    RIGHT           ; (xx0)
        goto    START

NORTH2                          ; (X > 0)
        btfsc   TEMP, 2         ; (1xx)
        goto    NORTH4          ; (1xx)
        call    LEFT            ; (0xx)
        goto    START

NORTH3
        btfss   TEMP, 1         ; (x11)
        call    FORWARD         ; (x01)
        btfsc   TEMP, 1         ; (x11)
        call    LEFT
        goto    START

NORTH4                          ; (1xx)
        btfss   TEMP,   1       ; (11x)?
        call    FORWARD         ; (10x)
        btfsc   TEMP, 1         ; (11x)?
        call    RIGHT           ; (10x)
        goto    START

;--------------------------------------------------------------
FORWARD
;--------------------------------------------------------------

        movlw   b'10100111'     ; L=Fwd, R=Fwd
        movwf   PORTB
        return

;--------------------------------------------------------------
REVERSE
;--------------------------------------------------------------

        movlw   b'01010111'     ; L=Rev, R=Rev
        movwf   PORTB
        return

;--------------------------------------------------------------
RIGHT
;--------------------------------------------------------------

        movlw   b'10010111'     ; L=Fwd, R=Rev
        movwf   PORTB
        incf    DIR, 1
        incf    RTLT, 1
        return

;--------------------------------------------------------------
LEFT
;--------------------------------------------------------------

        movlw   b'01100111'     ; L=Rev, R=Fwd
        movwf   PORTB
        decf    DIR, 1
        decf    RTLT, 1
        return

;---------------------- DELAY subroutine ---------------------

; The DELAY subroutine is used to delay the execution of the next
; command by a specific period as determined by the values of
; COUNTER1, COUNTER2 and COUNTER3

DELAY
        clrwdt
        movlw   0xC8            ; Set COUNTER1
        movwf   COUNTER1        ; to decimal 200

DELAY1
        movlw   0xC8            ; Set COUNTER2
        movwf   COUNTER2        ; to decimal 200

DELAY2
        movlw   0x0B            ; Set COUNTER3
        movwf   COUNTER3        ; to decimal 5

DELAY3
        decfsz  COUNTER3, 1
        goto    DELAY3

        decfsz  COUNTER2, 1
        goto    DELAY2

        decfsz  COUNTER1, 1
        goto    DELAY1
        return
        end
```

APPENDIX B
CIRCUIT DIAGRAMS

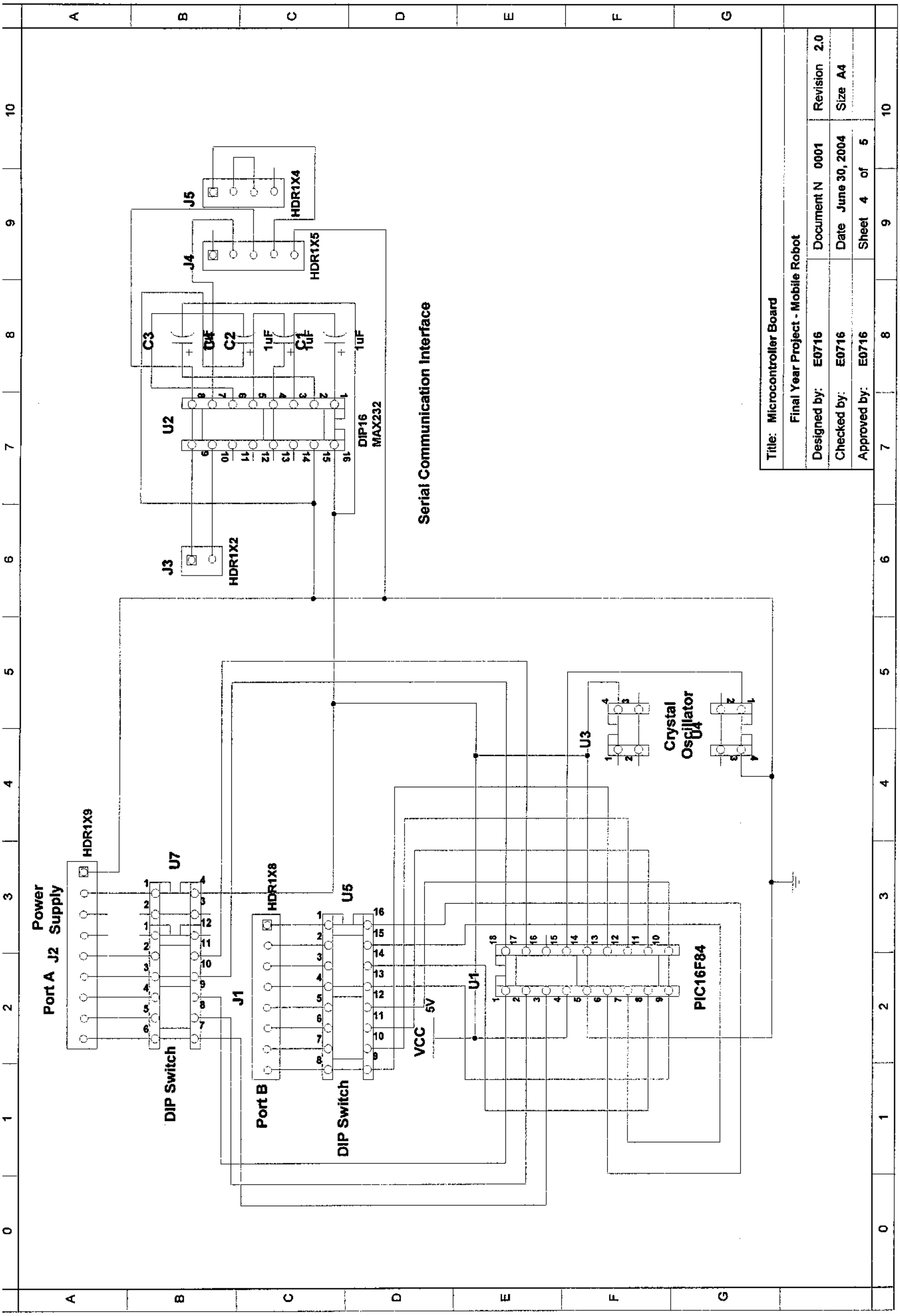

Title: Ultrasonic Sensor
Final Year Project - Mobile Robot
Designed by: E0716
Checked by: E0716
Approved by: E0716
Document N 0001
Date June 30, 2004
Sheet 1 of 6
Revision 2.0
Size A4
Power Supply
J3
HDR1X4
Signals
J4
HDR1X2
LED1
LED_blue
U2
LM311N
U5
LM567
U1
LM741CN
U3
LM555CN
Q1
2N3904
R1
R2
1.0kohm
R3
10kohm
R4
560ohm
R5
10kohm
R6
10kohm
R7
3.9kohm
R8
22kohm
R9
1.0Mohm
R10
R11
20kohm
R12
Key = a
10K_LIN
R13
330ohm
R14
1.0kohm
R16
1.0kohm
C1
1.0nF
C2
1.0nF
C3
1.0nF
C4
20nF
C5
10uF
VCC
5V
Transmitter (+)
Transmitter (-)
Receiver (+)
Receiver (-)
50%

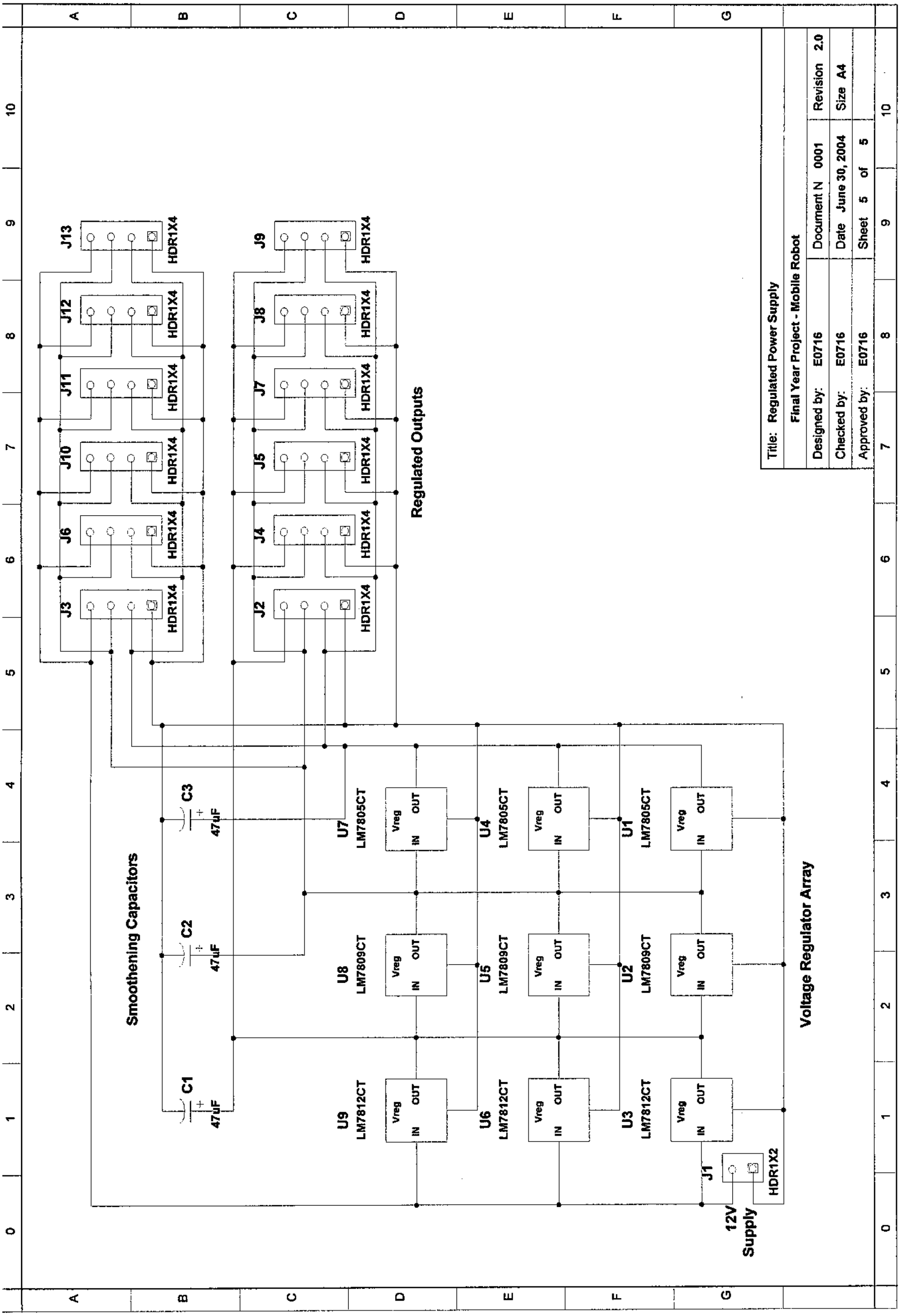


J4
HDR1X2
VDD
9V
Q1
2SC945
R1
150ohm
IR Transmitter
J3
HDR1X4
VDD
9V
R3
1.0kohm
Q2
2SC945
IR Receiver
Title: Infrared Transceiver Circuit
Final Year Project - Mobile Robot
Designed by: E0716
Document N 0001
Revision 2.0
Checked by: E0716
Date June 30, 2004
Size A4
Approved by: E0716
Sheet 2 of 6

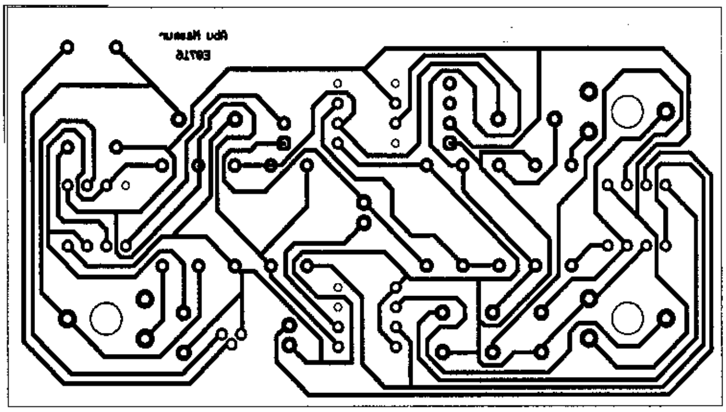


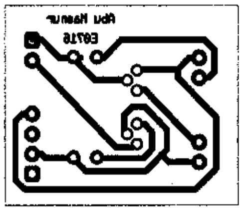
Title: Motor Control (H-Bridge Circuit)
Final Year Project - Mobile Robot
Designed by: E0716
Checked by: E0716
Approved by: E0716
Document N 0001
Date June 30, 2004
Sheet 3 of 6
Revision 2.0
Size A4
VDD 12V
VCC 5V
U1 LM311N
U2 LM311N
Q1 ZTX704
Q2 ZTX704
Q3 ZTX604
Q4 ZTX604
R1 470ohm
R2 470ohm
R3 1.0kohm
R4 10kohm
R5 10kohm
R6 10kohm
R7 470ohm
R8 1.0kohm
R9 10kohm
R10 10kohm
R11 10kohm
R12 470ohm
J1 HDR1X4
J4 HDR1X4
Power Supply
Control

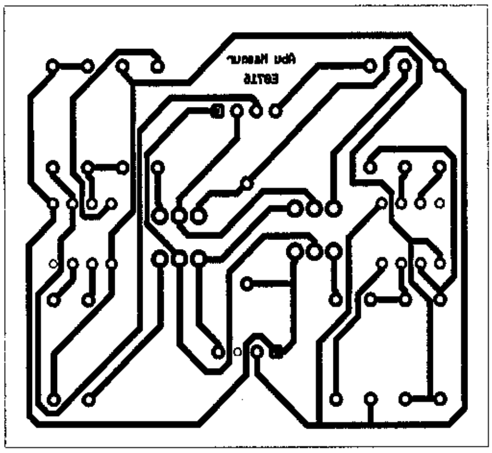

Serial Communication Interface
U2
DIP16
MAX232
J3
HDR1X2
J4
HDR1X5
J5
HDR1X4
C1
C2
C3
1uF
Power Supply
Port A J2
HDR1X9
U7
DIP Switch
J1
HDR1X8
Port B
U5
DIP Switch
VCC
5V
U1
PIC16F84
U3
Crystal Oscillator
U4
Title: Microcontroller Board
Final Year Project - Mobile Robot
Designed by: E0716
Checked by: E0716
Approved by: E0716
Document N 0001
Date June 30, 2004
Sheet 4 of 5
Revision 2.0
Size A4

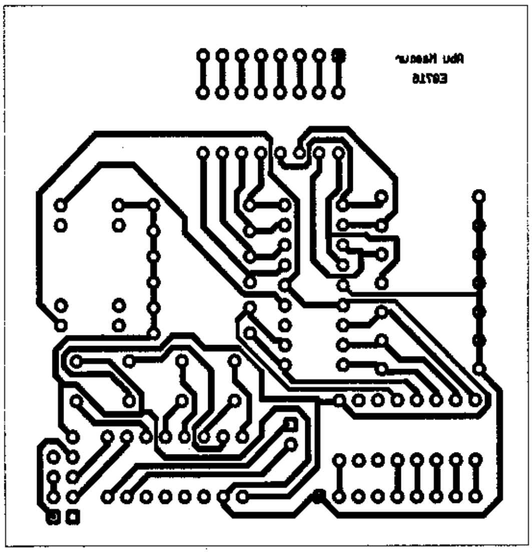

Title: Regulated Power Supply
Final Year Project - Mobile Robot
Designed by: E0716
Checked by: E0716
Approved by:
Document N 0001
Date June 30, 2004
Sheet 5 of 5
Revision 2.0
Size A4
Regulated Outputs
Smoothening Capacitors
Voltage Regulator Array
12V Supply
J1 HDR1X2
J2 J3 J4 J5 J6 J7 J8 J9 J10 J11 J12 J13 HDR1X4
C1 47uF
C2 47uF
C3 47uF
U1 LM7805CT
U2 LM7809CT
U3 LM7812CT
U4 LM7805CT
U5 LM7809CT
U6 LM7812CT
U7 LM7805CT
U8 LM7809CT
U9 LM7812CT
Vreg IN OUT

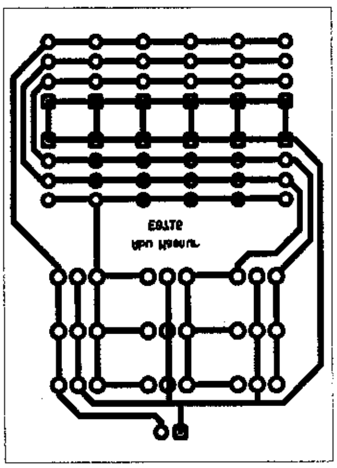
APPENDIX C
PCB LAYOUTS











APPENDIX D
DATASHEETS

National Semiconductor

January 2001

LM111/LM211/LM311 Voltage Comparator

General Description

The LM111, LM211 and LM311 are voltage comparators that have input currents nearly a thousand times lower than devices like the LM106 or LM710. They are also designed to operate over a wider range of supply voltages: from standard ±15V op amp supplies down to the single 5V supply used for IC logic. Their output is compatible with RTL, DTL and TTL as well as MOS circuits. Further, they can drive lamps or relays, switching voltages up to 50V at currents as high as 50 mA.

Both the inputs and the outputs of the LM111, LM211 or the LM311 can be isolated from system ground, and the output can drive loads referred to ground, the positive supply or the negative supply. Offset balancing and strobe capability are provided and outputs can be wire OR'ed. Although slower than the LM106 and LM710 (200 ns response time vs 40 ns) the devices are also much less prone to spurious oscillations. The LM111 has the same pin configuration as the LM106 and LM710.

The LM211 is identical to the LM111, except that its performance is specified over a −25°C to +85°C temperature range instead of −55°C to +125°C. The LM311 has a temperature range of 0°C to +70°C.

Features

- Operates from single 5V supply
- Input current: 150 nA max. over temperature
- Offset current: 20 nA max. over temperature
- Differential input voltage range: ±30V
- Power consumption: 135 mW at ±15V

Absolute Maximum Ratings for the LM311 (Note 12)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Total Supply Voltage (V_{84})	36V
Output to Negative Supply Voltage (V_{74})	40V
Ground to Negative Supply Voltage (V_{14})	30V
Differential Input Voltage	±30V
Input Voltage (Note 13)	±15V
Power Dissipation (Note 14)	500 mW
ESD Rating (Note 19)	300V
Output Short Circuit Duration	10 sec
Operating Temperature Range	0° to 70°C
Storage Temperature Range	−65°C to 150°C
Lead Temperature (soldering, 10 sec)	260°C
Voltage at Strobe Pin	V^+−5V
Soldering Information	
Dual-In-Line Package	
Soldering (10 seconds)	260°C
Small Outline Package	
Vapor Phase (60 seconds)	215°C
Infrared (15 seconds)	220°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

Electrical Characteristics (Note 15)

for the LM311

Parameter	Conditions	Min	Typ	Max	Units
Input Offset Voltage (Note 16)	T_A=25°C, R_S≤50k		2.0	7.5	mV
Input Offset Current(Note 16)	T_A=25°C		6.0	50	nA
Input Bias Current	T_A=25°C		100	250	nA
Voltage Gain	T_A=25°C	40	200		V/mV
Response Time (Note 17)	T_A=25°C		200		ns
Saturation Voltage	V_{IN}≤−10 mV, I_{OUT}=50 mA T_A=25°C		0.75	1.5	V
Strobe ON Current (Note 18)	T_A=25°C		2.0	5.0	mA
Output Leakage Current	V_{IN}≥10 mV, V_{OUT}=35V T_A=25°C, I_{STROBE}=3 mA V^- = Pin 1 = −5V		0.2	50	nA
Input Offset Voltage (Note 16)	R_S≤50K			10	mV
Input Offset Current (Note 16)				70	nA
Input Bias Current				300	nA
Input Voltage Range		−14.5	13.8,−14.7	13.0	V
Saturation Voltage	V^+≥4.5V, V^-=0 V_{IN}≤−10 mV, I_{OUT}≤8 mA		0.23	0.4	V
Positive Supply Current	T_A=25°C		5.1	7.5	mA
Negative Supply Current	T_A=25°C		4.1	5.0	mA

Note 12: "Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits."

Note 13: This rating applies for ±15V supplies. The positive input voltage limit is 30V above the negative supply. The negative input voltage limit is equal to the negative supply voltage or 30V below the positive supply, whichever is less.

Note 14: The maximum junction temperature of the LM311 is 110°C. For operating at elevated temperature, devices in the H08 package must be derated based on a thermal resistance of 165°C/W, junction to ambient, or 20°C/W, junction to case. The thermal resistance of the dual-in-line package is 100°C/W, junction to ambient.

Note 15: These specifications apply for V_S=±15V and Pin 1 at ground, and 0°C < T_A < +70°C, unless otherwise specified. The offset voltage, offset current and bias current specifications apply for any supply voltage from a single 5V supply up to ±15V supplies.

Note 16: The offset voltages and offset currents given are the maximum values required to drive the output within a volt of either supply with 1 mA load. Thus, these parameters define an error band and take into account the worst-case effects of voltage gain and R_S.

Note 17: The response time specified (see definitions) is for a 100 mV input step with 5 mV overdrive.

Note 18: This specification gives the range of current which must be drawn from the strobe pin to ensure the output is properly disabled. Do not short the strobe pin to ground; it should be current driven at 3 to 5 mA.

Note 19: Human body model, 1.5 kΩ in series with 100 pF.

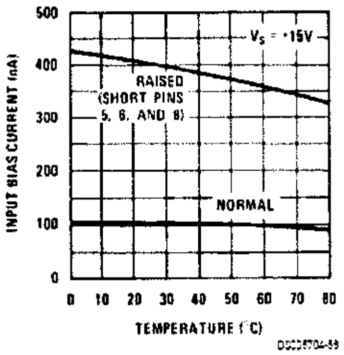
National Semiconductor

January 2001

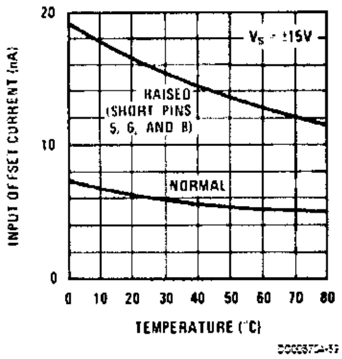
LM111/LM211/LM311
Voltage Comparator

LM311 Typical Performance Characteristics

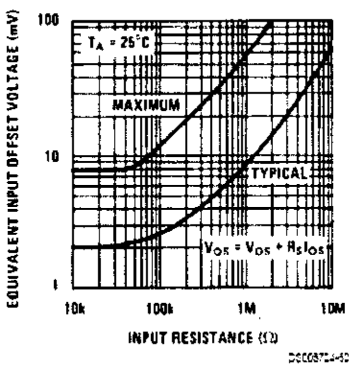
Input Bias Current



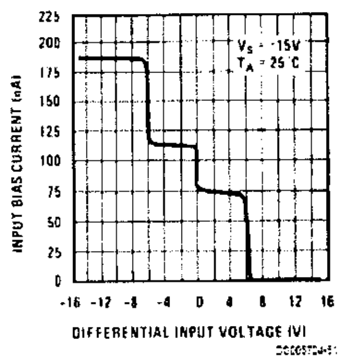
Input Offset Current



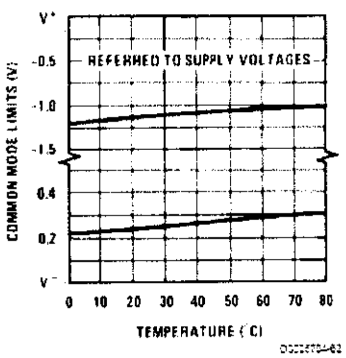
Offset Error



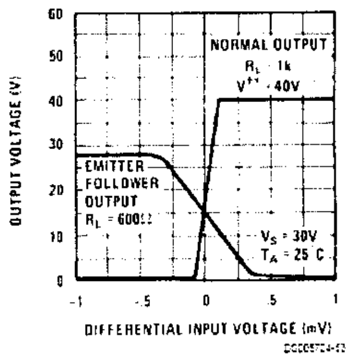
Input Characteristics



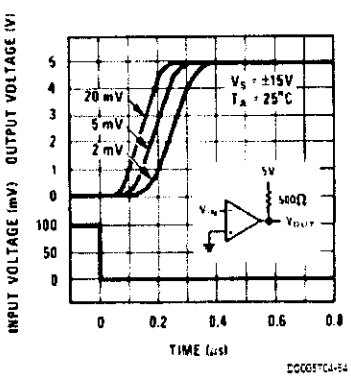
Common Mode Limits



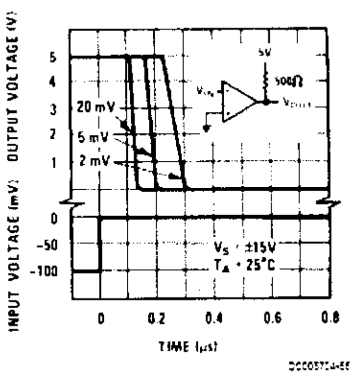
Transfer Function



Response Time for Various Input Overdrives

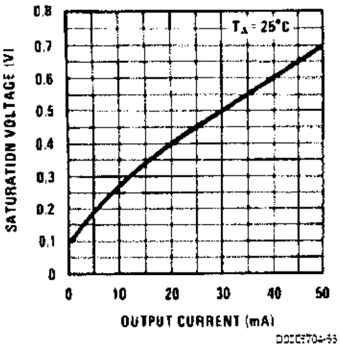


Response Time for Various Input Overdrives

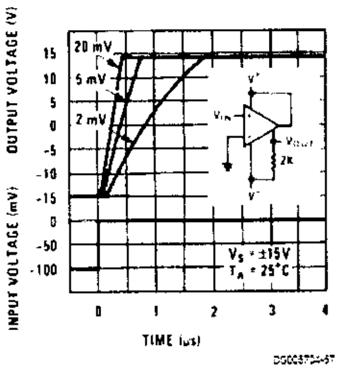


LM311 Typical Performance Characteristics (Continued)

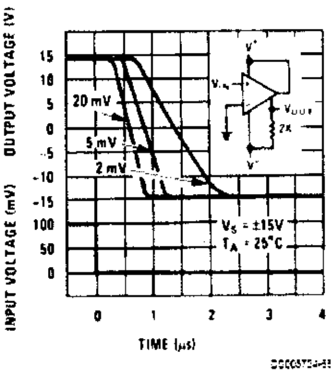
Output Saturation Voltage



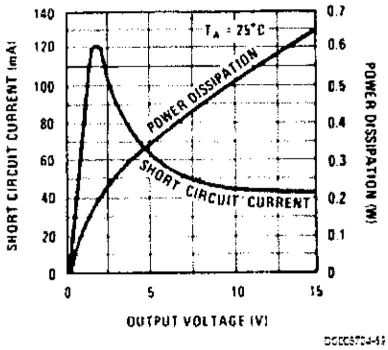
Response Time for Various Input Overdrives



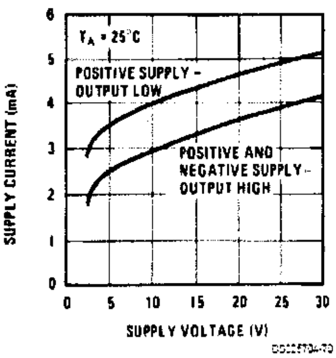
Response Time for Various Input Overdrives



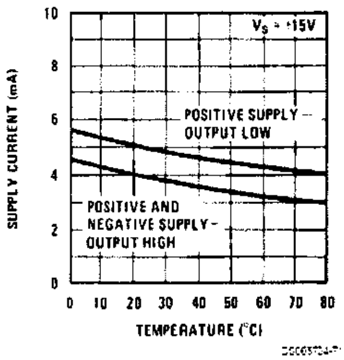
Output Limiting Characteristics



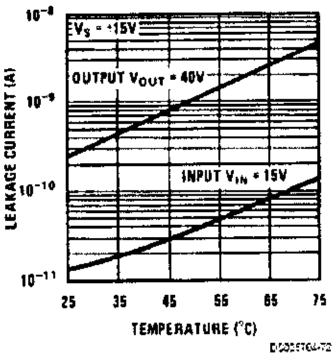
Supply Current



Supply Current



Leakage Currents



National Semiconductor

February 2000

LM555
Timer

General Description

The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For astable operation as an oscillator, the free running frequency and duty cycle are accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output circuit can source or sink up to 200mA or drive TTL circuits.

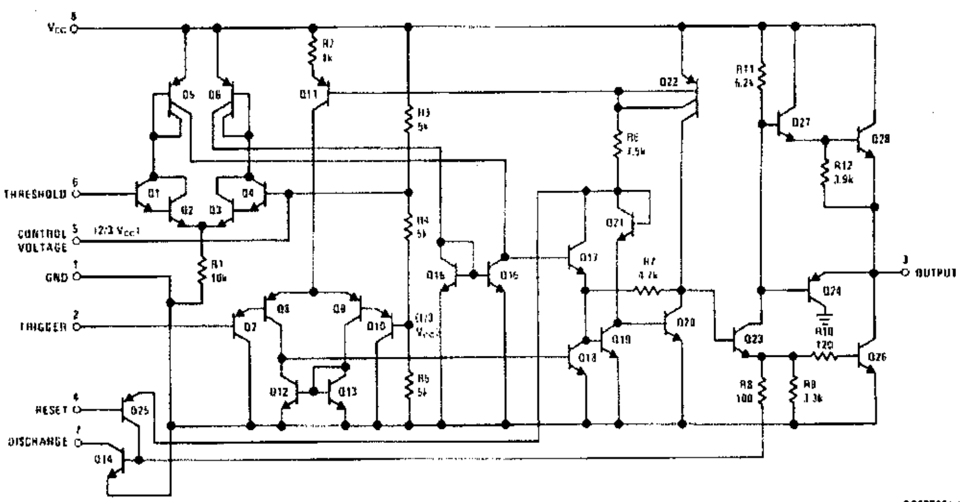
Features

- Direct replacement for SE555/NE555
- Timing from microseconds through hours
- Operates in both astable and monostable modes
- Adjustable duty cycle
- Output can source or sink 200 mA
- Output and supply TTL compatible
- Temperature stability better than 0.005% per °C
- Normally on and normally off output
- Available in 8-pin MSOP package

Applications

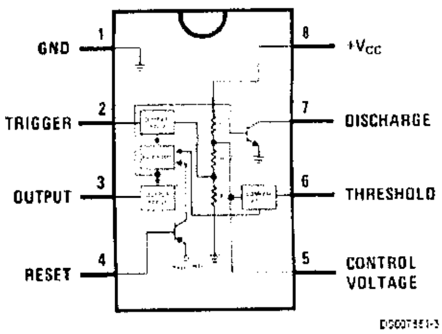
- Precision timing
- Pulse generation
- Sequential timing
- Time delay generation
- Pulse width modulation
- Pulse position modulation
- Linear ramp generator

Schematic Diagram



Connection Diagram

Dual-In-Line, Small Outline and Molded Mini Small Outline Packages



Top View

Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Supply Voltage	+18V
Power Dissipation (Note 3)	
LM555CM, LM555CN	1180 mW
LM555CMM	613 mW
Operating Temperature Ranges	
LM555C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C
Soldering Information	
Dual-In-Line Package	
Soldering (10 Seconds)	260°C
Small Outline Packages (SOIC and MSOP)	
Vapor Phase (60 Seconds)	215°C
Infrared (15 Seconds)	220°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

Electrical Characteristics (Notes 1, 2)

(T_A = 25°C, V_{CC} = +5V to +15V, unless othewise specified)

Parameter	Conditions	Limits LM555C			Units
		Min	Typ	Max	
Supply Voltage		4.5		16	V
Supply Current	V_{CC} = 5V, R_L = ∞		3	6	mA
	V_{CC} = 15V, R_L = ∞ (Low State) (Note 4)		10	15	
Timing Error, Monostable					
Initial Accuracy			1		%
Drift with Temperature	R_A = 1k to 100kΩ, C = 0.1µF, (Note 5)		50		ppm/°C
Accuracy over Temperature			1.5		%
Drift with Supply			0.1		%/V
Timing Error, Astable					
Initial Accuracy			2.25		%
Drift with Temperature	R_A, R_B = 1k to 100kΩ, C = 0.1µF, (Note 5)		150		ppm/°C
Accuracy over Temperature			3.0		%
Drift with Supply			0.30		%/V
Threshold Voltage			0.667		x V_{CC}
Trigger Voltage	V_{CC} = 15V		5		V
	V_{CC} = 5V		1.67		V
Trigger Current			0.5	0.9	µA
Reset Voltage		0.4	0.5	1	V
Reset Current			0.1	0.4	mA
Threshold Current	(Note 6)		0.1	0.25	µA
Control Voltage Level	V_{CC} = 15V	9	10	11	V
	V_{CC} = 5V	2.6	3.33	4	
Pin 7 Leakage Output High			1	100	nA
Pin 7 Sat (Note 7)					
Output Low	V_{CC} = 15V, I_7 = 15mA		180		mV
Output Low	V_{CC} = 4.5V, I_7 = 4.5mA		80	200	mV
Output Voltage Drop (Low)	V_{CC} = 15V				
	I_{SINK} = 10mA		0.1	0.25	V
	I_{SINK} = 50mA		0.4	0.75	V
	I_{SINK} = 100mA		2	2.5	V
	I_{SINK} = 200mA		2.5		V
	V_{CC} = 5V				
	I_{SINK} = 8mA				V
	I_{SINK} = 5mA		0.25	0.35	V
Output Voltage Drop (High)	I_{SOURCE} = 200mA, V_{CC} = 15V		12.5		V
	I_{SOURCE} = 100mA, V_{CC} = 15V	12.75	13.3		V
	V_{CC} = 5V	2.75	3.3		V
Rise Time of Output			100		ns
Fall Time of Output			100		ns

Note 1: All voltages are measured with respect to the ground pin, unless otherwise specified.

Note 2: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits. Electrical Characteristics state DC and AC electrical specifications under particular test conditions which guarantee specific performance limits. This assumes that the device is within the Operating Ratings. Specifications are not guaranteed for parameters where no limit is given, however, the typical value is a good indication of device performance.

Note 3: For operating at elevated temperatures the device must be derated above 25°C based on a +150°C maximum junction temperature and a thermal resistance of 106°C/W (DIP), 170°C/W (SO-8) and 204°C/W (MSOP) junction to ambient.

Note 4: Supply current when output high typically 1 mA less at V_{CC} = 5V.

Note 5: Tested at V_{CC} = 5V and V_{CC} = 15V.

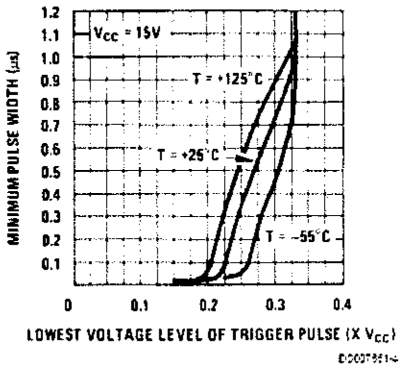
Note 6: This will determine the maximum value of $R_A + R_B$ for 15V operation. The maximum total ($R_A + R_B$) is 20MΩ.

Note 7: No protection against excessive pin 7 current is necessary providing the package dissipation rating will not be exceeded.

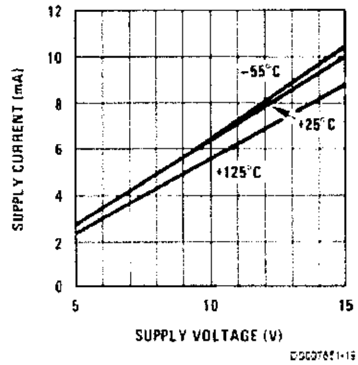
Note 8: Refer to RETS555X drawing of military LM555H and LM555J versions for specifications.

Typical Performance Characteristics

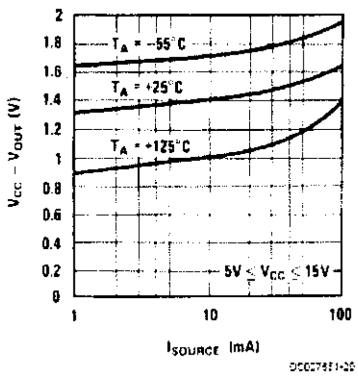
Minimuim Pulse Width
Required for Triggering



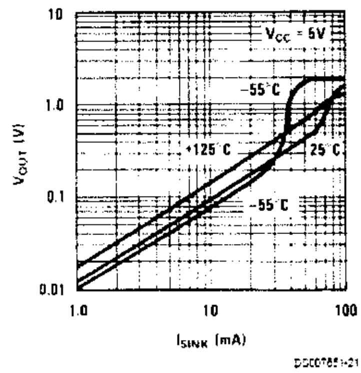
Supply Current vs.
Supply Voltage



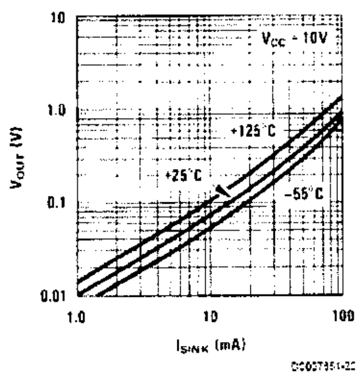
High Output Voltage vs.
Output Source Current



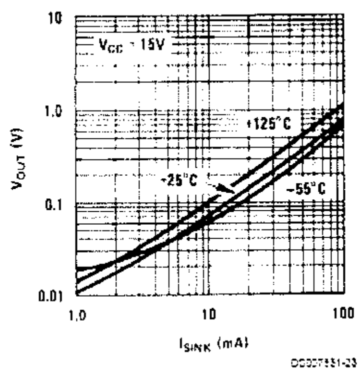
Low Output Voltage vs.
Output Sink Current



Low Output Voltage vs.
Output Sink Current

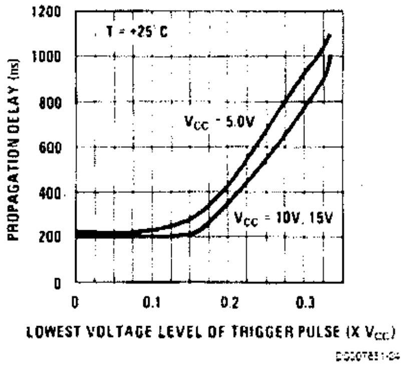


Low Output Voltage vs.
Output Sink Current

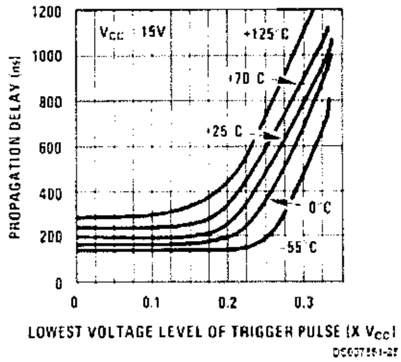


Typical Performance Characteristics (Continued)

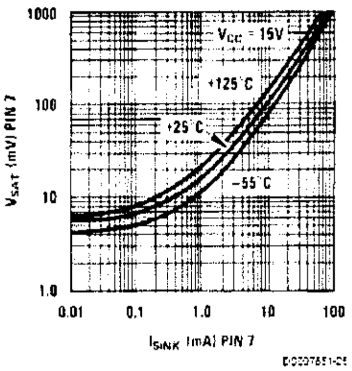
Output Propagation Delay vs. Voltage Level of Trigger Pulse



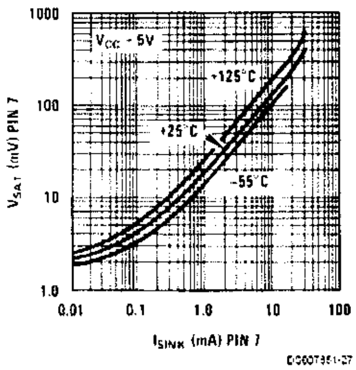
Output Propagation Delay vs. Voltage Level of Trigger Pulse



Discharge Transistor (Pin 7) Voltage vs. Sink Current



Discharge Transistor (Pin 7) Voltage vs. Sink Current



National Semiconductor

May 1999

LM567/LM567C
Tone Decoder

General Description

The LM567 and LM567C are general purpose tone decoders designed to provide a saturated transistor switch to ground when an input signal is present within the passband. The circuit consists of an I and Q detector driven by a voltage controlled oscillator which determines the center frequency of the decoder. External components are used to independently set center frequency, bandwidth and output delay.

Features

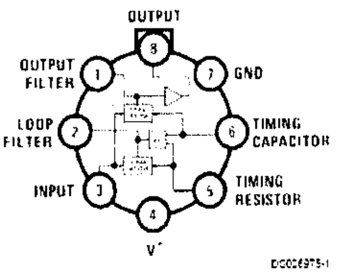
- 20 to 1 frequency range with an external resistor
- Logic compatible output with 100 mA current sinking capability
- Bandwidth adjustable from 0 to 14%
- High rejection of out of band signals and noise
- Immunity to false signals
- Highly stable center frequency
- Center frequency adjustable from 0.01 Hz to 500 kHz

Applications

- Touch tone decoding
- Precision oscillator
- Frequency monitoring and control
- Wide band FSK demodulation
- Ultrasonic controls
- Carrier current remote controls
- Communications paging decoders

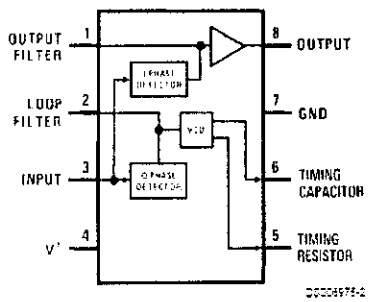
Connection Diagrams

Metal Can Package



Top View
Order Number LM567H or LM567CH
See NS Package Number H08C

Dual-In-Line and Small Outline Packages



Top View
Order Number LM567CM
See NS Package Number M08A
Order Number LM567CN
See NS Package Number N08E

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Supply Voltage Pin	9V
Power Dissipation (Note 2)	1100 mW
V_8	15V
V_3	−10V
V_3	V_4 + 0.5V
Storage Temperature Range	−65°C to +150°C

Operating Temperature Range	
LM567H	−55°C to +125°C
LM567CH, LM567CM, LM567CN	0°C to +70°C
Soldering Information	
Dual-In-Line Package	
Soldering (10 sec.)	260°C
Small Outline Package	
Vapor Phase (60 sec.)	215°C
Infrared (15 sec.)	220°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

Electrical Characteristics

AC Test Circuit, T_A = 25°C, V^+ = 5V

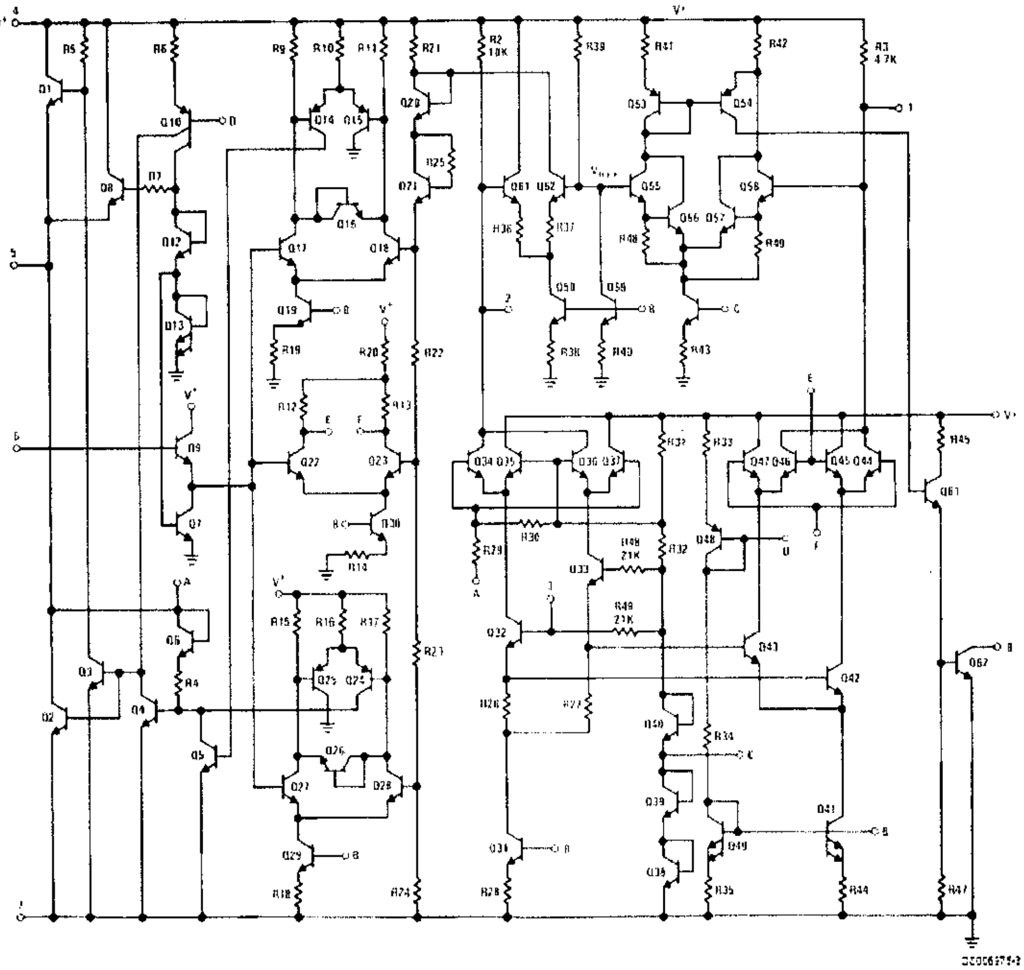
Parameters	Conditions	LM567			LM567C/LM567CM			Units
		Min	Typ	Max	Min	Typ	Max	
Power Supply Voltage Range		4.75	5.0	9.0	4.75	5.0	9.0	V
Power Supply Current Quiescent	R_L = 20k		6	8		7	10	mA
Power Supply Current Activated	R_L = 20k		11	13		12	15	mA
Input Resistance		18	20		15	20		kΩ
Smallest Detectable Input Voltage	I_L = 100 mA, $f_i = f_o$		20	25		20	25	mVrms
Largest No Output Input Voltage	I_C = 100 mA, $f_i = f_o$	10	15		10	15		mVrms
Largest Simultaneous Outband Signal to Inband Signal Ratio			6			6		dB
Minimum Input Signal to Wideband Noise Ratio	B_n = 140 kHz		−6			−6		dB
Largest Detection Bandwidth		12	14	16	10	14	18	% of f_o
Largest Detection Bandwidth Skew			1	2		2	3	% of f_o
Largest Detection Bandwidth Variation with Temperature			±0.1			±0.1		%/°C
Largest Detection Bandwidth Variation with Supply Voltage	4.75–6.75V		±1	±2		±1	±5	%V
Highest Center Frequency		100	500		100	500		kHz
Center Frequency Stability (4.75–5.75V)	0 < T_A < 70 −55 < T_A < +125		35 ± 60 35 ± 140			35 ± 60 35 ± 140		ppm/°C ppm/°C
Center Frequency Shift with Supply Voltage	4.75V–6.75V 4.75V–9V		0.5	1.0 2.0		0.4	2.0 2.0	%/V %/V
Fastest ON-OFF Cycling Rate			f_o/20			f_o/20		
Output Leakage Current	V_8 = 15V		0.01	25		0.01	25	µA
Output Saturation Voltage	e_i = 25 mV, I_8 = 30 mA e_i = 25 mV, I_8 = 100 mA		0.2 0.6	0.4 1.0		0.2 0.6	0.4 1.0	V
Output Fall Time			30			30		ns
Output Rise Time			150			150		ns

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits. Electrical Characteristics state DC and AC electrical specifications under particular test conditions which guarantee specific performance limits. This assumes that the device is within the Operating Ratings. Specifications are not guaranteed for parameters where no limit is given, however, the typical value is a good indication of device performance.

Note 2: The maximum junction temperature of the LM567 and LM567C is 150°C. For operating at elevated temperatures, devices in the TO-5 package must be derated based on a thermal resistance of 150°C/W, junction to ambient or 45°C/W, junction to case. For the DIP the device must be derated based on a thermal resistance of 110°C/W, junction to ambient. For the Small Outline package, the device must be derated based on a thermal resistance of 160°C/W, junction to ambient.

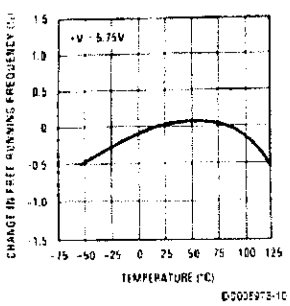
Note 3: Refer to RETS567X drawing for specifications of military LM567H version.

Schematic Diagram

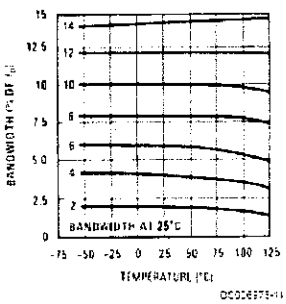


Typical Performance Characteristics

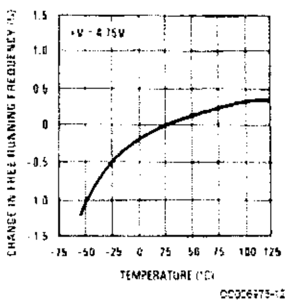
Typical Frequency Drift



Typical Bandwidth Variation

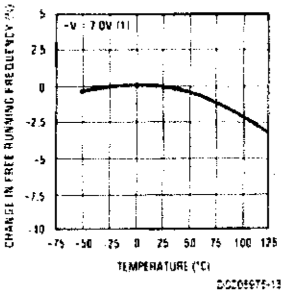


Typical Frequency Drift

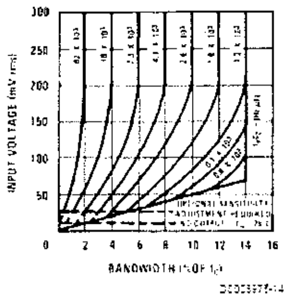


Typical Performance Characteristics (Continued)

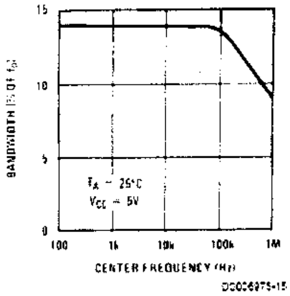
Typical Frequency Drift



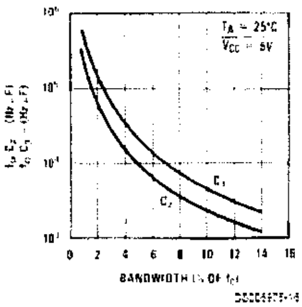
Bandwidth vs Input Signal Amplitude



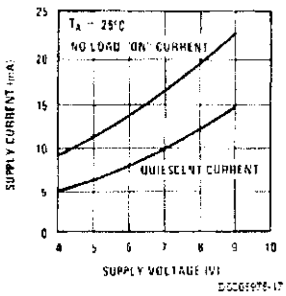
Largest Detection Bandwidth



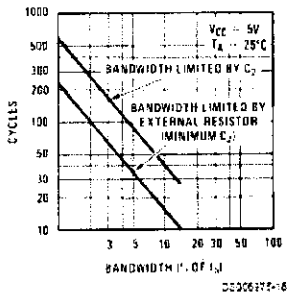
Detection Bandwidth as a Function of C_2 and C_3



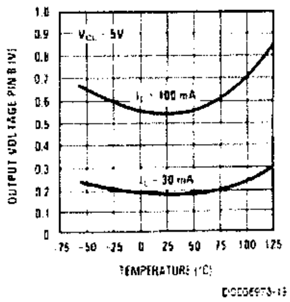
Typical Supply Current vs Supply Voltage



Greatest Number of Cycles Before Output



Typical Output Voltage vs Temperature



National Semiconductor

August 2000

LM741
Operational Amplifier

General Description

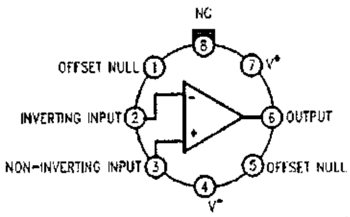
The LM741 series are general purpose operational amplifiers which feature improved performance over industry standards like the LM709. They are direct, plug-in replacements for the 709C, LM201, MC1439 and 748 in most applications.

The amplifiers offer many features which make their application nearly foolproof: overload protection on the input and output, no latch-up when the common mode range is exceeded, as well as freedom from oscillations.

The LM741C is identical to the LM741/LM741A except that the LM741C has their performance guaranteed over a 0°C to +70°C temperature range, instead of −55°C to +125°C.

Connection Diagrams

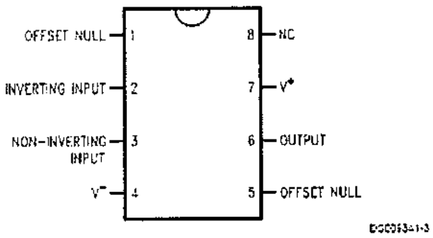
Metal Can Package



Note 1: LM741H is available per JM38510/10101

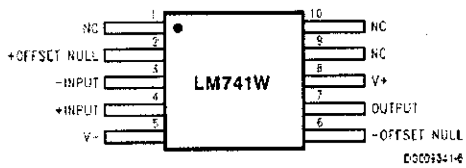
Order Number LM741H, LM741H/883 (Note 1), **LM741AH/883 or LM741CH**
See NS Package Number H08C

Dual-In-Line or S.O. Package



Order Number LM741J, LM741J/883, LM741CN
See NS Package Number J08A, M08A or N08E

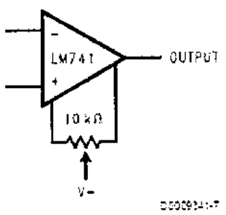
Ceramic Flatpak



Order Number LM741W/883
See NS Package Number W10A

Typical Application

Offset Nulling Circuit



Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

(Note 7)

	LM741A	LM741	LM741C
Supply Voltage	±22V	±22V	±18V
Power Dissipation (Note 3)	500 mW	500 mW	500 mW
Differential Input Voltage	±30V	±30V	±30V
Input Voltage (Note 4)	±15V	±15V	±15V
Output Short Circuit Duration	Continuous	Continuous	Continuous
Operating Temperature Range	−55°C to +125°C	−55°C to +125°C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C	−65°C to +150°C	−65°C to +150°C
Junction Temperature	150°C	150°C	100°C
Soldering Information			
N-Package (10 seconds)	260°C	260°C	260°C
J- or H-Package (10 seconds)	300°C	300°C	300°C
M-Package			
Vapor Phase (60 seconds)	215°C	215°C	215°C
Infrared (15 seconds)	215°C	215°C	215°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

	LM741A	LM741	LM741C
ESD Tolerance (Note 8)	400V	400V	400V

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	T_A = 25°C										
	$R_S \le 10$ kΩ					1.0	5.0		2.0	6.0	mV
	$R_S \le 50Ω$		0.8	3.0							mV
	$T_{AMIN} \le T_A \le T_{AMAX}$										
	$R_S \le 50Ω$			4.0							mV
	$R_S \le 10$ kΩ						6.0			7.5	mV
Average Input Offset Voltage Drift				15							μV/°C
Input Offset Voltage Adjustment Range	T_A = 25°C, V_S = ±20V	±10				±15			±15		mV
Input Offset Current	T_A = 25°C		3.0	30		20	200		20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			70		85	500			300	nA
Average Input Offset Current Drift				0.5							nA/°C
Input Bias Current	T_A = 25°C		30	80		80	500		80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			0.210			1.5			0.8	μA
Input Resistance	T_A = 25°C, V_S = ±20V	1.0	6.0		0.3	2.0		0.3	2.0		MΩ
	$T_{AMIN} \le T_A \le T_{AMAX}$, V_S = ±20V	0.5									MΩ
Input Voltage Range	T_A = 25°C							±12	±13		V
	$T_{AMIN} \le T_A \le T_{AMAX}$				±12	±13					V
Large Signal Voltage Gain	T_A = 25°C, $R_L \ge 2$ kΩ										
	V_S = ±20V, V_O = ±15V	50									V/mV
	V_S = ±15V, V_O = ±10V				50	200		20	200		V/mV
	$T_{AMIN} \le T_A \le T_{AMAX}$, $R_L \ge 2$ kΩ,										
	V_S = ±20V, V_O = ±15V	32									V/mV
	V_S = ±15V, V_O = ±10V				25			15			V/mV
	V_S = ±5V, V_O = ±2V	10									V/mV
Output Voltage Swing	V_S = ±20V										
	$R_L \ge 10$ kΩ	±16									V
	$R_L \ge 2$ kΩ	±15									V
	V_S = ±15V										
	$R_L \ge 10$ kΩ				±12	±14		±12	±14		V
	$R_L \ge 2$ kΩ				±10	±13		±10	±13		V
Output Short Circuit Current	T_A = 25°C	10	25	35		25			25		mA
	$T_{AMIN} \le T_A \le T_{AMAX}$	10		40							mA
Common-Mode Rejection Ratio	$T_{AMIN} \le T_A \le T_{AMAX}$										
	$R_S \le 10$ kΩ, V_{CM} = ±12V				70	90		70	90		dB
	$R_S \le 50Ω$, V_{CM} = ±12V	80	95								dB

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Supply Voltage Rejection Ratio	$T_{AMIN} \le T_A \le T_{AMAX}$, $V_S = \pm 20V$ to $V_S = \pm 5V$										
	$R_S \le 50\Omega$	86	96								dB
	$R_S \le 10\ k\Omega$				77	96		77	96		dB
Transient Response	$T_A = 25°C$, Unity Gain										
Rise Time			0.25	0.8		0.3			0.3		μs
Overshoot			6.0	20		5			5		%
Bandwidth (Note 6)	$T_A = 25°C$	0.437	1.5								MHz
Slew Rate	$T_A = 25°C$, Unity Gain	0.3	0.7			0.5			0.5		V/μs
Supply Current	$T_A = 25°C$					1.7	2.8		1.7	2.8	mA
Power Consumption	$T_A = 25°C$										
	$V_S = \pm 20V$		80	150							mW
	$V_S = \pm 15V$					50	85		50	85	mW
LM741A	$V_S = \pm 20V$										
	$T_A = T_{AMIN}$			165							mW
	$T_A = T_{AMAX}$			135							mW
LM741	$V_S = \pm 15V$										
	$T_A = T_{AMIN}$					60	100				mW
	$T_A = T_{AMAX}$					45	75				mW

Note 2: "Absolute Maximum Ratings" indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits.

Note 3: For operation at elevated temperatures, these devices must be derated based on thermal resistance, and T_j max. (listed under "Absolute Maximum Ratings"). $T_j = T_A + (\theta_{jA} P_D)$.

Thermal Resistance	Cerdip (J)	DIP (N)	HO8 (H)	SO-8 (M)
θ_{jA} (Junction to Ambient)	100°C/W	100°C/W	170°C/W	195°C/W
θ_{jC} (Junction to Case)	N/A	N/A	25°C/W	N/A

Note 4: For supply voltages less than ±15V, the absolute maximum input voltage is equal to the supply voltage.

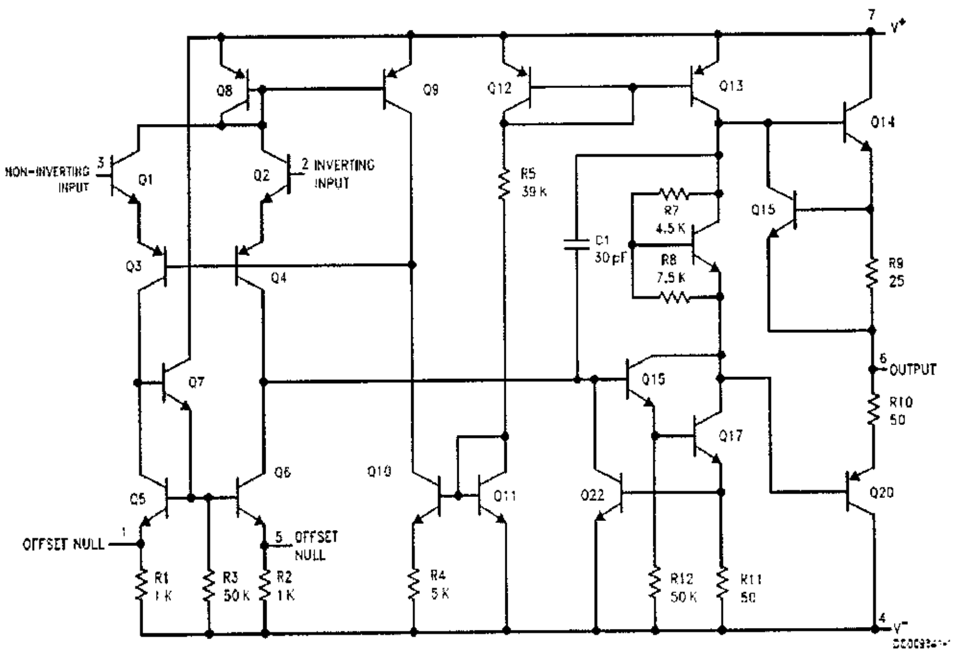
Note 5: Unless otherwise specified, these specifications apply for $V_S = \pm 15V$, $-55°C \le T_A \le +125°C$ (LM741/LM741A). For the LM741C/LM741E, these specifications are limited to $0°C \le T_A \le +70°C$.

Note 6: Calculated value from: BW (MHz) = 0.35/Rise Time(μs)

Note 7: For military specifications see RETS741X for LM741 and RETS741AX for LM741A.

Note 8: Human body model, 1.5 kΩ in series with 100 pF.

Schematic Diagram

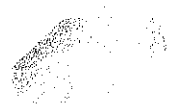


FAIRCHILD
SEMICONDUCTOR™

TIP31 Series(TIP31/31A/31B/31C)

Medium Power Linear Switching Applications

- Complementary to TIP32/32A/32B/32C



1 TO-220

1.Base 2.Collector 3.Emitter

NPN Epitaxial Silicon Transistor

Absolute Maximum Ratings T_C=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector-Base Voltage : TIP31	40	V
	: TIP31A	60	V
	: TIP31B	80	V
	: TIP31C	100	V
V_{CEO}	Collector-Emitter Voltage : TIP31	40	V
	: TIP31A	60	V
	: TIP31B	80	V
	: TIP31C	100	V
V_{EBO}	Emitter-Base Voltage	5	V
I_C	Collector Current (DC)	3	A
I_{CP}	Collector Current (Pulse)	5	A
I_B	Base Current	1	A
P_C	Collector Dissipation (T_C=25°C)	40	W
P_C	Collector Dissipation (T_a=25°C)	2	W
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	- 65 ~ 150	°C

Electrical Characteristics T_C=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
$V_{CEO}(sus)$	* Collector-Emitter Sustaining Voltage				
	: TIP31	I_C = 30mA, I_B = 0	40		V
	: TIP31A		60		V
	: TIP31B		80		V
	: TIP31C		100		V
I_{CEO}	Collector Cut-off Current				
	: TIP31/31A	V_{CE} = 30V, I_B = 0		0.3	mA
	: TIP31B/31C	V_{CE} = 60V, I_B = 0		0.3	mA
I_{CES}	Collector Cut-off Current				
	: TIP31	V_{CE} = 40V, V_{EB} = 0		200	μA
	: TIP31A	V_{CE} = 60V, V_{EB} = 0		200	μA
	: TIP31B	V_{CE} = 80V, V_{EB} = 0		200	μA
	: TIP31C	V_{CE} = 100V, V_{EB} = 0		200	μA
I_{EBO}	Emitter Cut-off Current	V_{EB} = 5V, I_C = 0		1	mA
h_{FE}	* DC Current Gain	V_{CE} = 4V, I_C = 1A	25		
		V_{CE} = 4V, I_C = 3A	10	50	
$V_{CE}(sat)$	* Collector-Emitter Saturation Voltage	I_C = 3A, I_B = 375mA		1.2	V
$V_{BE}(sat)$	* Base-Emitter Saturation Voltage	V_{CE} = 4V, I_C = 3A		1.8	V
f_T	Current Gain Bandwidth Product	V_{CE} = 10V, I_C = 500mA	3.0		MHz

* Pulse Test: PW≤300μs, Duty Cycle≤2%

Typical Characteristics

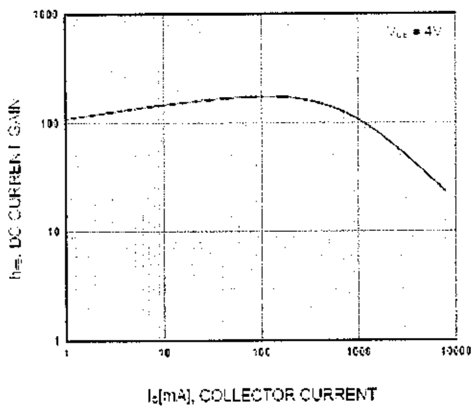


Figure 1. DC current Gain

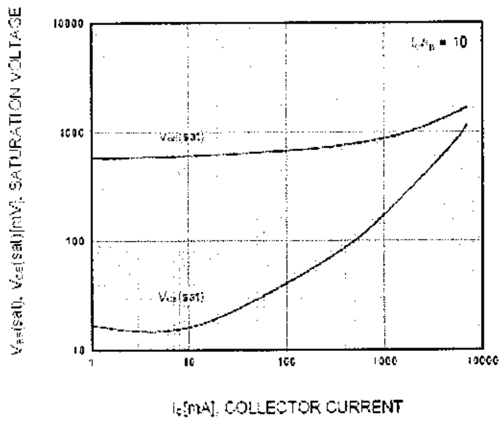


Figure 2. Base-Emitter Saturation Voltage
Collector-Emitter Saturation Voltage

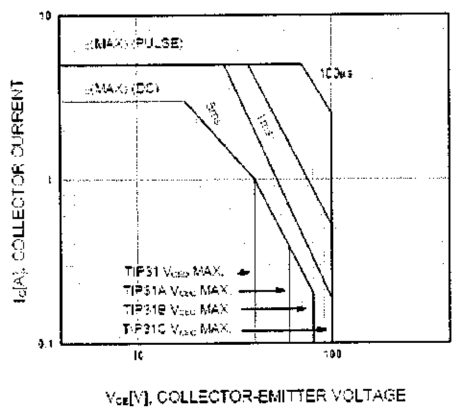


Figure 3. Safe Operating Area

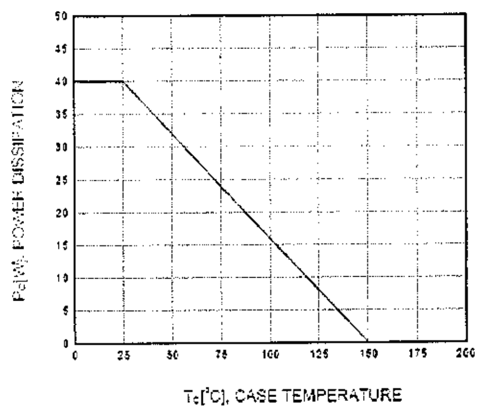


Figure 4. Power Derating

Typical Characteristics

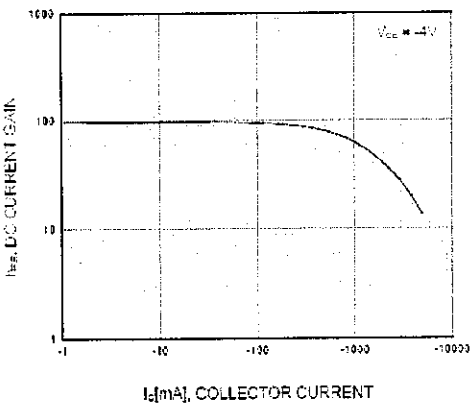


Figure 1. DC current Gain

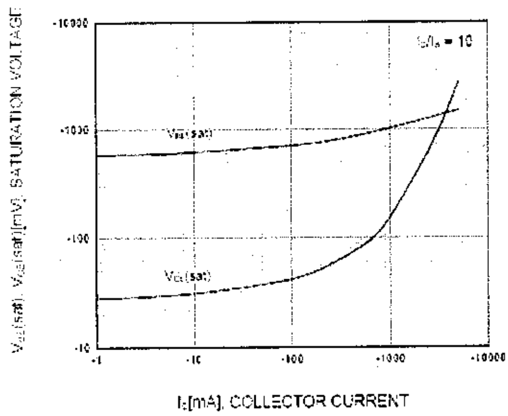


Figure 2. Base-Emitter Saturation Voltage Collector-Emitter Saturation Voltage

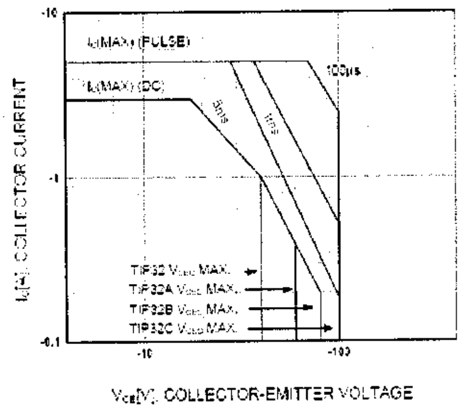


Figure 3. Safe Operating Area

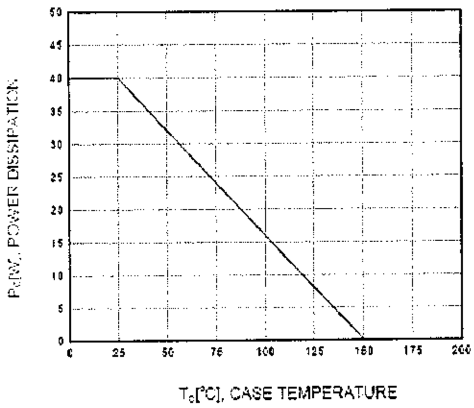


Figure 4. Power Derating

FAIRCHILD
SEMICONDUCTOR

TIP32 Series(TIP32/32A/32B/32C)

Medium Power Linear Switching Applications

- Complement to TIP31/31A/31B/31C

1 TO-220

1.Base 2.Collector 3.Emitter

PNP Epitaxial Silicon Transistor

Absolute Maximum Ratings T_C=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector-Base Voltage : TIP32	- 40	V
	: TIP32A	- 60	V
	: TIP32B	- 80	V
	: TIP32C	- 100	V
V_{CEO}	Collector-Emitter Voltage : TIP32	- 40	V
	: TIP32A	- 60	V
	: TIP32B	- 80	V
	: TIP32C	-100	V
V_{EBO}	Emitter-Base Voltage	- 5	V
I_C	Collector Current (DC)	- 3	A
I_{CP}	Collector Current (Pulse)	- 5	A
I_B	Base Current	- 3	A
P_C	Collector Dissipation (T_C=25°C)	40	W
P_C	Collector Dissipation (T_a=25°C)	2	W
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	- 65 ~ 150	°C

Electrical Characteristics T_C=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Max.	Units
V_{CEO}(sus)	* Collector-Emitter Sustaining Voltage				
	: TIP32	I_C = - 30mA, I_B = 0	-40		V
	: TIP32A		-60		V
	: TIP32B		-80		V
	: TIP32C		-100		V
I_{CEO}	Collector Cut-off Current				
	: TIP32/32A	V_{CE} = - 30V, I_B = 0		- 0.3	mA
	: TIP32B/32C	V_{CE} = - 60V, I_B = 0		- 0.3	mA
I_{CES}	Collector Cut-off Current				
	: TIP32	V_{CE} = - 40V, V_{EB} = 0		- 200	μA
	: TIP32A	V_{CE} = - 60V, V_{EB} = 0		- 200	μA
	: TIP32B	V_{CE} = - 80V, V_{EB} = 0		- 200	μA
	: TIP32C	V_{CE} = - 100V, V_{CE} = 0		- 200	μA
I_{EBO}	Emitter Cut-off Current	V_{EB} = - 5V, I_C = 0		- 1	mA
h_{FE}	* DC Current Gain	V_{CE} = - 4V, I_C = - 1A	25		
		V_{CE} = - 4V, I_C = - 3A	10	50	
V_{CE}(sat)	* Collector-Emitter Saturation Voltage	I_C = - 3A, I_B = - 375mA		- 1.2	V
V_{BE}(sat)	* Base-Emitter Saturation Voltage	V_{CE} = - 4V, I_C = - 3A		- 1.8	V
f_T	Current Gain Bandwidth Product	V_{CE} = - 10V, I_C = - 500mA	3.0		MHz

* Pulse Test: PW≤300μs, Duty Cycle≤2%