Department of Electronic and Telecommunication Engineering

University of Moratuwa

EN 2090 – Laboratory Practice II

Analog Line Following Robot

Project Report

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This project report is submitted in partial fulfillment of the requirements for the module EN 2090: Laboratory Practice II.

1. Abstract

Line following robot is an autonomous robot which has the capability to follow a white line on a black surface or vice versa. In this project we have been given to design an analog line following robot which should follow a 3 cm wide white line on a black surface and the robot has to stop, when it sees a perpendicular white line to the path that it follows. Generally, these kind of autonomous line following robots are made using micro-controllers such as PIC or Atmega. But our task is to build a fully functional analog line following robot without using such micro-controllers. Therefore we are supposed to build this robot using only Op Amps, IR sensors and a motor driving IC. Thus we have to design our own schematics for each and every circuit in order to accomplish our task.

2. Introduction

Line following robot is one of the basic robotics projects which is ideal as a beginner project for the students who are interested in robotics. The usual approach of designing a line following robot is to choose a micro controller like Arduino, take readings from a sensor panel, process them and drive the motors accordingly using a control system such as PID (Proportional, Derivative and Integral Control System). The success of the project mainly relies upon the algorithm or the code which we have to modify several times during the debugging phase.

In our project, the task was to build an analog line follower in which we can't use any microcontrollers or programmable ICs (Integrated Circuits). It is solely made of analog components such as Op Amps, Resistors, Capacitors, Potentiometers, IR (Infrared) sensors and non-programmable ICs. The signal processing part which was done by the micro controller has to be carried out by using basic Op amp circuit like amplifiers, adders and subtractors. Since we cannot modify the behaviour using an algorithm (code) later, everything has to be designed carefully from the very beginning.

In our analog line following robot we take readings from a sensor panel using IR sensors and those sensor readings are combined with different gains to generate an error signal. After that, the error signal is processed using a PID controller circuit and the signals for the two motors are processed using Op Amp circuits. The two outputs are compared with a triangular waveform to generate PWM signals which are fed to the motor driver to rotate the two motors independently, following the white line.

The whole system forms a closed loop with feedback where each motor is driven according to the sensor readings. It is important to perform calculations at each step to select the correct values for components like resistors and capacitors. Sensors need to be calibrated for accurate functionality. The behaviour of the robot can be modified from the potentiometers used alongside with the PID controller circuit.

2.1 Objectives

- Designing an IR sensor panel to track the white line.
- Designing an analog system to process the sensor inputs.
- Designing a motor driver circuit to drive the motors and designing a stop condition circuit.
- Designing a power supply for powering the robot.
- Modifying a pre made robot chassis according to our requirements.
- Assembling all the components with a good finishing.
- Optimizing the performance while lowering the cost.
- Detecting the mistakes and errors and debugging.

2.2 Robot specifications

- Chassis:- Pre made robot chassis modified as per our requirements
- Length:- 18cm
- Width:- 15cm
- Height:- 14cm
- Weight:- 800g (approximately)
- Power:- 11.1V Lipo Battery (850mAh)
  9V DC Battery
- Motors:- 6V 190rpm DC Motors

2.3 Arena

The arena for the analog line following robot is a normal line following platform with a 3cm white line on a black background. The two surfaces should reflect IR with a clear difference in the readings.

3. METHOD

3.1 Bill of Materials

3.1.1 Sensor Panel Circuit

- TCRT5000 IR Sensor - 6
- LM324N Quad Op Amp IC - 2
- 10K Potentiometer - 1
- 100Ω resistors - 6
- 4.7k resistors - 6
- Connectors

3.1.2 Error Signal Circuit

- LM324N Quad Op Amp IC - 1
- Blue LED - 6
- 330Ω resistors - 6
- 10k resistors - 5
- 12k resistors - 2
- 18k resistors - 2
- 33k resistors - 2
- Connectors

3.1.3 Triangular Waveform Circuit

- LM324N Quad Op Amp IC - 1
- 0.1uF mylar capacitor - 2
- 100k resistors - 1
- 15k resistors -1
- 33k resistors - 1
- 47k resistors – 2
- Connectors

3.1.4 PID Controller Circuit

- LM324N Quad Op Amp IC - 1
- 10K Potentiometer - 3
- 0.1uF mylar capacitor - 2
- 10k resistors - 8
- 20k resistors - 1
- Connectors

3.1.5 Motor Controller Circuit

- LM324N Quad Op Amp IC - 2
- 10K Potentiometer - 1
- 0.1uF mylar capacitor – 1
- 10k resistors - 15
- 18k resistors – 2
- Connectors

3.1.6 Motor Driver and Stop Condition Circuit

- L293d Motor Driver IC - 1
- 74LS08 Quad 2-input AND Gate IC – 1
- Connectors

3.1.7 Power Supply Circuit

- LM7809 9V Regulator IC - 1
- LM7805 5V Regulator IC - 1
- 0.1uF mylar capacitor - 4
- 100uF electrolytic capacitor – 4
- Connectors

3.1.8 Other components

- Robot Chassis - 1
- 6V 190 rpm DC Motors – 2
- Wheels - 2
- 11.1V 850mAh Lipo Battery
- 9V DC Battery
- 3mm Spacing, Nuts and Bolts
- Metal Eyeball Castor Wheel
- 2 pin Switch – 2
- Double Tape
- Jumper Wires

3.1.9 Tools

- Multi-meter
- Soldering Iron
- De-soldering Sucker
- Solder
- Glue Gun
- Oscilloscope
- Screw Driver
- Wire Cutter
- PCB Drill
- Pair of Scissors

3.2 Control Loop

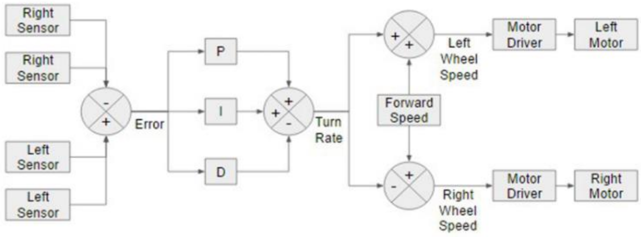

Figure 1 – Control Loop

Source: - http://www.will-moore.com/analog-line-follower

The intention of a line follower robot is to follow a line. In order to do that it needs to identify its current location with respect to the line. Then it should rotate its motors accordingly such that its centre is aligned with the line. 6 TCRT5000 IR sensors are used in the sensor panel to identify the robot's current location with respect to the line. Each of these sensors outputs an analog voltage depending on how much it sees the line based on the IR reflection principles on surfaces with different colours.

Then all sensor outputs are converted into digital signals using Op Amp comparators. These digital signals are combined with different gains to generate the error signal. Error is zero if the robot is positioned the middle of the line and error is negative and positive respectively in the left and right sides of the line. The magnitude of the error is proportional to the deviation of the robot from the line.

Once we have the error signal, that signal is fed to the PID circuit. The job of the PID circuit is to convert the error signal into a desired action or response while smoothing the motion of the robot without overshooting. The PID circuit consists of three parts; Proportional Control, Derivative Control and Integral Control. Then we have to transform the adjustment signal (output of the PID circuit) in to a turn rate, that we can turn the robot towards the line until the robot is positioned at the middle of the line with a zero error.

Robot has two wheels controlled by two 6V DC motors. In order to turn the robot, the adjustment signal must be added to the base speed of left motor and it should be subtracted from the base speed of the right motor respectively. Base speed is the speed of the robot when it perfectly aligns with the line. If it is required to turn the robot right, the left wheel speed should be greater than the right wheel speed and vice versa.

Analog signals and analog currents in the control loop are not enough to drive motors. Hence we need to use a motor driver to drive the two motors. Thus the above turn rates are converted into PWM signals by comparing them with a triangular waveform. These PWM signals are fed to the two motors using the motor driver. The relative position of the white line and the sensor panel is continuously changing with the robot movement. Therefore above mentioned procedure repeats over and over.

The above mentioned tasks require many mathematical functions for which we used a microcontroller in normal line followers. In the analog line follower Op Amp ICs are used for operations like comparison, amplification (giving gains), addition, subtraction, integration and differentiation. In our project we used LM324N IC which has four operational amplifiers.

3.2.1 LM324N Quad Op Amp IC

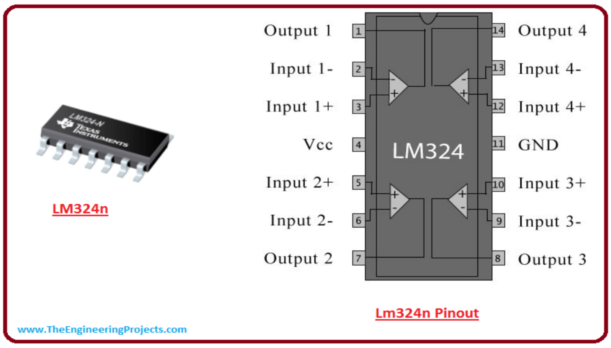

Figure 2 – LM324N IC

Source: - https://www.theengineeringprojects.com

LM324N consists of four operational amplifiers which can be used for designing simple op amp circuits. Both positive and negative supply voltages can be given as per our requirements. It is a low cost IC which is sufficient for our intended applications here.

3.2.2 Stop Condition

The digital outputs of two sensors at the edges will be 1 when it sees a perpendicular line to the line it follows. At all other times only one edge sensor can be 1. Therefore it is possible use a logical circuit to switch off the two motors when both edge sensors give digital 1 output. This is achieved by a logical AND IC and the motor controller IC.

3.3 Circuit Design

3.3.1 Sensor Panel

The line following sensor panel consists of six TCRT5000 IR sensors. TCRT 5000 IR sensor has an IR emitting LED coupled with a phototransistor. The IR emitter can be activated by sending a current through it. The current should be in between 20mA and 40mA for the correct functionality. Therefore the current was limited by applying a 100Ω resistor in series with the IR emitting LED. (Figure 4)

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Figure 3 - TCRT5000 IR Sensor

Source: - http://bdspeedytech.com

When the IR emitting LED is powered it emits an IR beam which is reflected by surfaces. Black and white surfaces reflect IR at different amounts. It depends on the type of the surface as well. The reflected IR beam is incident on the phototransistor. The IR intensity control the current through the phototransistor. Therefore it is possible to have an analog voltage output for different IR intensities by attaching a pull up resistor to the collector.

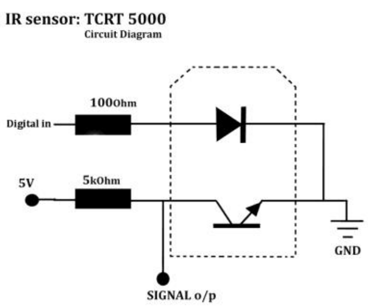

Figure 4 – Connecting a TCRT 5000 Sensor

Source: - http://www.instructables.com/id/Using-IR-Sensor-TCRT-5000-With-Arduino-and-Program/

In a line following robot it is preferred to have a digital output (0V and 5V) for black and white. Therefore the analog output of the sensor is compared with a threshold voltage using Op Amp comparator circuits made by LM324 ICs. This threshold voltage needs to be changed according to the environment conditions. Therefore a 10K Potentiometer is used to set the threshold voltage.

4.7k resistors are used as pull up resistors and threshold around 1.6V is set for all the comparators. The 6 sensors are placed 0.75cm apart each other except the two middle sensors are placed aligning with the two edges of the 3cm line. Two LM324 Op Amp ICs are used to build the 6 comparators. The sensor panel is mounted in a separate PCB. 6 connectors are used to connecting the 6 digital outputs. Additional two connectors are used to connect the sensors at the two edges into the stop condition circuit. The sensor panel should be placed near to the line following surface for the proper functionality.

3.3.2 Error Signal Circuit

The digital outputs of the 6 sensors are connected to 6 blue LEDs to indicate the status of the sensor which will be useful for debugging purposes. 6 330Ω resistors are used to limit the current through LEDs.

Two scaling adders (Figure 5) designed using LM324 Op Amps are used to add the digital outputs of the two sides separately with different gains. Since it's required to have two polarities on the two sides the output of the right adder is used as an input of the left adder with a unity gain. Therefore it's possible to have negative voltages for left sensors and possible voltage for right sensors in the error signal which is the output of the left adder.

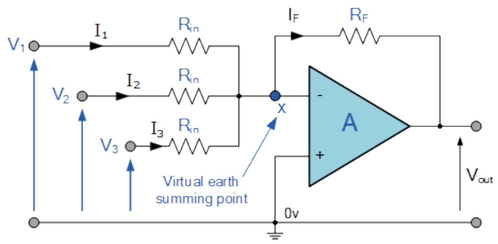

Figure 5 – Scaling Adder

Source: - https://www.electronics-tutorials.ws/opamp/opamp_4.html

The magnitude of the error is set proportional to the deviation from the line. This is achieved by applying different gains to the different sensor outputs. 10k resistors are used as feedback resistors while 12k, 15k, 18k resistors are used as input resistors (-0.83, -0.66, -0.55 gains respectively).

Error signal = (-0.83)*S1 + (-0.66)*S2 + (-0.55)*S3 + (0.55)*S4 + (0.66)*S5 + (0.83)*S6

Here S1 to S6 represents the digital voltage outputs (0V or 5V) of the six sensors from left to right. Edge sensors are given with a 0.83 gain while middle sensors are given with a 0.55 gain. Supply voltages of 9V and -9V are given to the LM324 OP Amps. Error signal represents the position of the robot with respect to the line. For convenience the error signal circuit is mounted with the triangular waveform circuit in the same PCB.

3.3.3 Triangular Waveform Circuit

The triangular waveform is generated by using the Schmitt Trigger circuit (Figure 6). It consists of two LM324 Op Amps. The first Op Amp generates a square wave. The second Op Amp integrates the square wave resulting a triangular waveform.

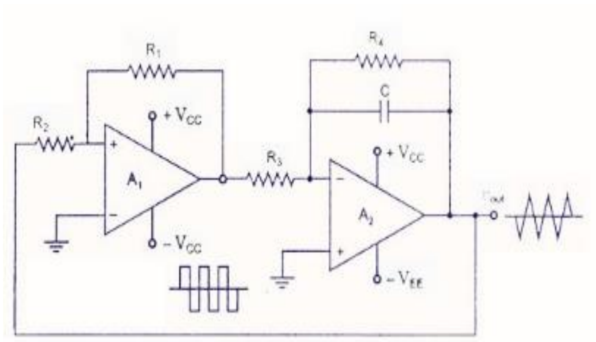

Figure 6 – Triangular Waveform Circuit

Source: - http://www.circuitstoday.com/triangular-waveform-using-schmitt-trigger

The characteristics of the triangular waveform such as frequency, peak to peak voltage and mean can be changed by varying the resistor values and capacitor values. We adjusted the resistor and capacitor values to generate a triangular waveform with 5V peak-peak, 4V mean and 290 Hz frequency which is desirable for the PWM generation purpose. For convenience the triangular waveform circuit is mounted with the error signal circuit in the same PCB.

3.3.4 PID Control Circuit

The error signal is controlled by a PID controller for a smooth motion reducing overshoots. The PID controller consists of three parts; Proportional Control, Derivative Control and Integral Control.

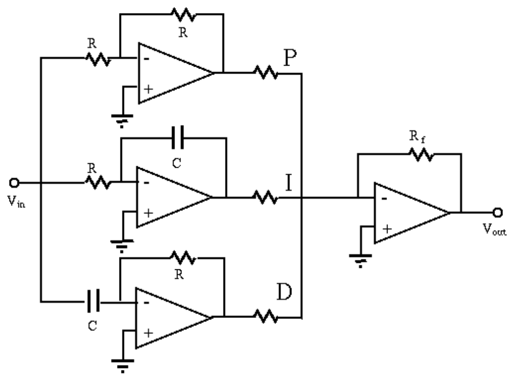

Figure 7 – PID controller

Source: - http://fourier.eng.hmc.edu/e84/lectures/opamp/node3.html

The proportional output is generated by an Op Amp inverting amplifier while the derivative output is generated by an Op Amp differentiator and the integral output is generated by an Op Amp integrator. (Figure 7) In the analog line follower it is required to change the proportional, derivative and integral constants in the tuning phase. Therefore the above 3 outputs are fed into 10k potentiometers before getting summed together. Then it is possible to change the required portions of the 3 outputs by adjusting the potentiometers based on the voltage divider concept.

The 3 controller outputs are summed together using an Op Amp scaling adder (Figure 5) to generate the adjustment signal. The polarities get inverted after the PID part and they switch back to the original ones after the operation of the summing amplifier. Supply voltages of 9V and -9V are given to the LM324 OP Amps. In practice it is difficult to tune a line following robot using integral control. Therefore a separate switch is added to switch off the integral controller. For convenience the PID controller circuit is mounted with the motor controller circuit in the same PCB.

3.3.5. Motor Controller Circuit

The base speed of the line following robot can be controlled by adjusting a 10k potentiometer set between 9V and 0V. A 0.1uF capacitor is added to enable soft start.

The adjustment signal must be added to the base speed of left motor and it should be subtracted from the base speed of the right motor respectively. These two tasks are carried out by Op Amp scaling adder (Figure 5) and Op Amp subtractor (Figure 8). Supply voltages of 9V and -9V are given to the LM324 OP Amps.

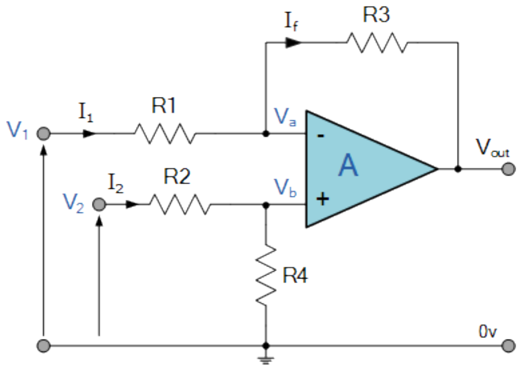

Figure 8 - Op Amp Subtractor

Source: - https://www.electronictutorials.ws/opamp/opamp_5.html

The two motor driving signals are fed into the motors as PWM (Pulse Width Modulation) Signals. To convert them into PWM signals the outputs of the above adder and the subtractor are compared with the triangular waveform. (Figure 9)

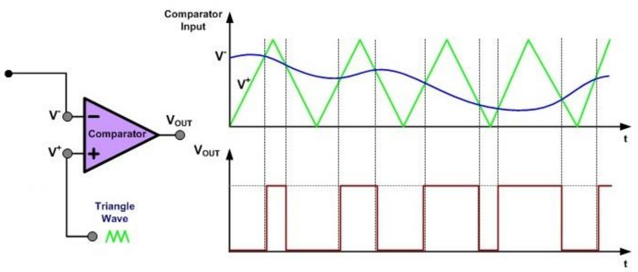

Figure 9 – PWM generation

Source: -http://www.ermicro.com/blog/?p=1908

The PWM frequency is determined by the frequency of the triangular wave. Since the triangular waveform is gradually rising up and down, comparing a constant DC voltage will result in a PWM signal with constant duty cycle. The duty cycle is increased and decreased when the voltage level goes up and down as shown in the figure 9. The two voltage levels of the high and low states are the supply voltages to the ICs, in our design 9V and 0V.

Since it's required to have a 5V PWM signal for the motor driver input the left and right PWM signals are first amplified with an inverting amplifier having a gain close to 0.55 (5/9) and to have the same polarity the signals are amplified with a unity gain inverting amplifier afterwards. For convenience the motor controller circuit is mounted with the PID controller circuit in the same PCB.

3.3.6. Motor Driver and Stop Condition Circuit

Since the analog currents are not sufficient to drive the motors a separate L293d motor controller IC (Figure 10) is used. This is a dual motor H bridge motor controller with enable inputs. Left and Right PWM signals are given to the enable inputs and 10 pattern is given as the inputs for the motors to continuously rotate the motors to the front. PWM signals which are generated according to the sensor inputs control the speed of the two motors in a way the robot follows the line. 6V is given as the supply voltage since the two motors have 6V rated voltage.

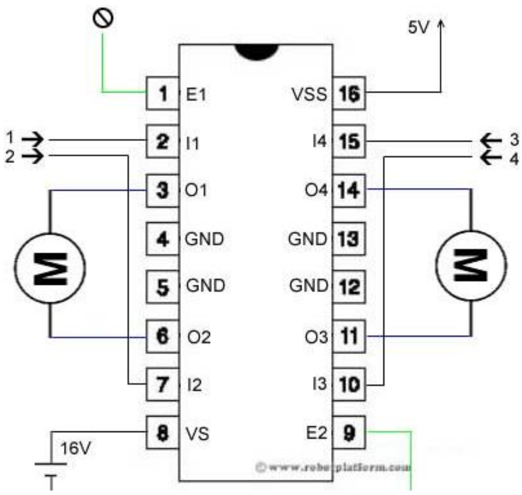

Figure 10 – L293d motor controller

Source: - http://www.robotplatform.com/howto/L293/motor_driver_1.html

The robot has to stop when it come across with a white line perpendicular to the following line. In such a situation sensors at both edges will be high. In all other situations at least one of the edge sensors are low. Therefore the digital outputs are logically AND using a 74LS08 AND gate IC (Figure 11) and the output is connected as one input signal for both motors replacing 0 while maintaining 1 at the other input signal.

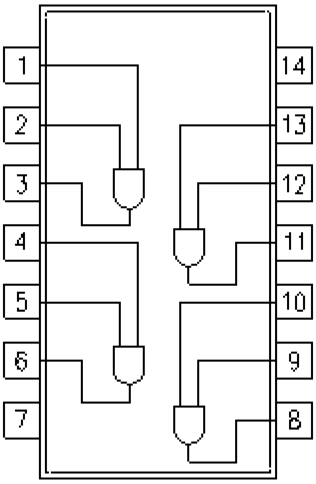

Figure 11 – 7408 AND Gate IC

Source: - https://www.futurlec.com/74/IC7408.shtml

Then in normal conditions two edge sensors cannot be high which results in logical 0 in the AND gate output. Then the pattern is 10 to the motors which means they continuously rotate in the front direction. When the robot encounters with a perpendicular white line both edge sensors will be high resulting logical 1 in the AND gate output. Then the pattern 11 is given to the motor controller which means the both motors will brake and the robot will stop. For convenience the motor driver and stop condition circuit is mounted with the power supply circuit in the same PCB.

3.3.7. Power Supply Circuit

Above mentioned circuits require different voltages for operation 5V, 9V and –9V. Positive 5V and 9V voltages are generated by regulating the 11.1 nominal voltage of the 3 cell Lipo battery using LM7805 and LM7809 ICs (Figure 12). -9V voltage is generated by a 9V DC Battery since it’s not used for high current applications. Connectors are used to distribute the required voltages to the other circuits. For convenience the power supply circuit is mounted with the motor driver and stop condition circuit in the same PCB.

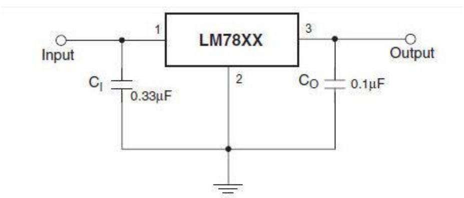

Figure 12 – LM78XX Regulator

Source: - http://www.datsun2000.com/tech/dash_regulator/

3.4 Robot Design

The above mentioned circuits were designed using Altium Designer as 4 separate PCBs (Printed Circuit Boards); sensor panel, error signal and triangular waveform, PID control and motor control, motor driver including stop condition and power supply. The PCBs were printed by a separate manufacturer and drilled and soldered by ourselves. Circuit schematics and PCB layouts are attached in the Appendix.

A pre made robot chassis (Figure 13) was bought and modified according to our requirements using spacing, nuts, bolts and required tools. 6V 190rpm DC motors are used for rotating the wheels and a separate caster wheel is used for balancing. An 11.1V 850mAh Lipo battery and a 9V DC Battery is used for powering purposes alongside with two switches. PCBs and other components were assembled together using a glue gun, and double tape. Jumper wires were used for connecting the 4 PCBs.

Figure 13 – Robot Chassis

Source: - https://www.lelong.com.my

4. RESULTS

Designing and implementing an analog line follower difficult robot is a complex task. Therefore we divided it into sub tasks. Each circuit design was initially tested on breadboards. Then the PCBs were printed step by step. Each PCB was tested to ensure proper working and debugged. Finally all the components were assembled together.

4.1 Sensor Panel

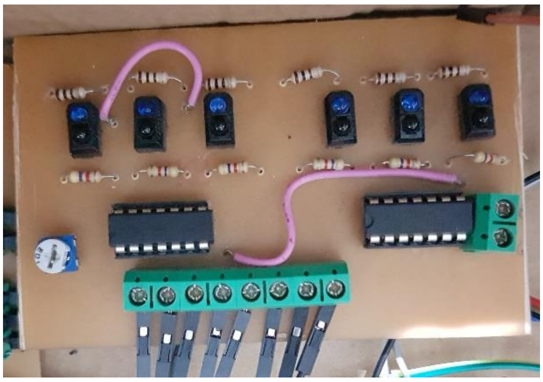

Figure 14 – PCB of the Sensor Panel

4.2 Error Signal and Triangular Waveform Circuit

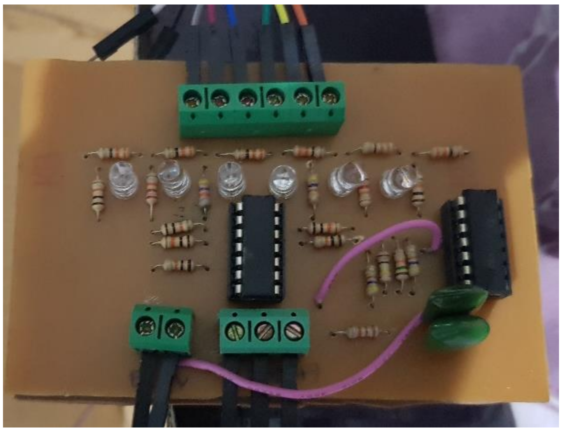

Figure 15 – PCB of the Triangular Waveform and Error Signal Circuit

After printing these two PCBs we checked their functionality using an Oscilloscope.

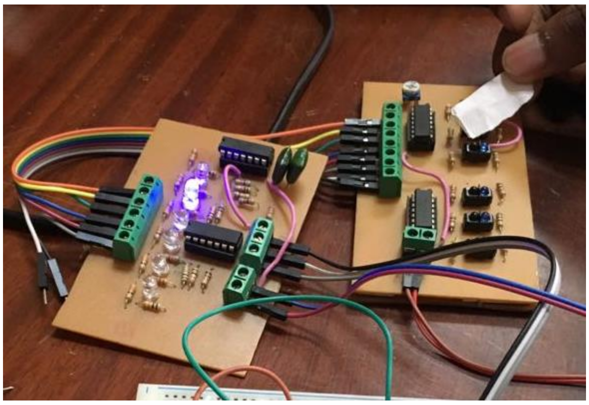

Figure 16 – Testing of the first two PCBs

The Sensor Panel circuit was functioning properly since the LEDs lit according to the sensor inputs.

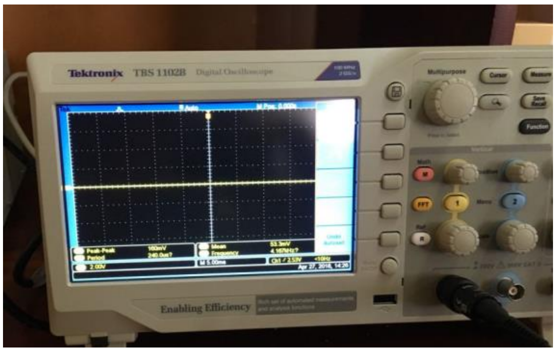

Figure 17 – Error signal when the line is in the middle of the sensor panel

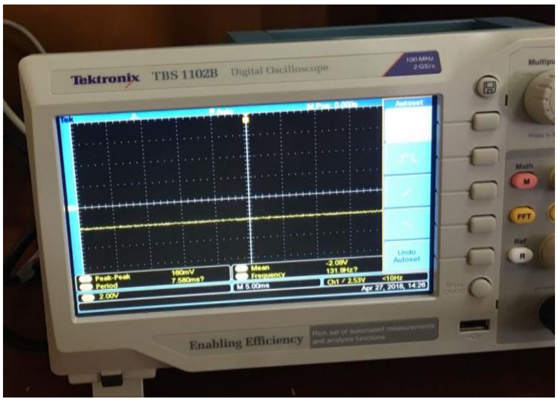

Figure 18 – Error signal when the line is in the left side of the sensor panel

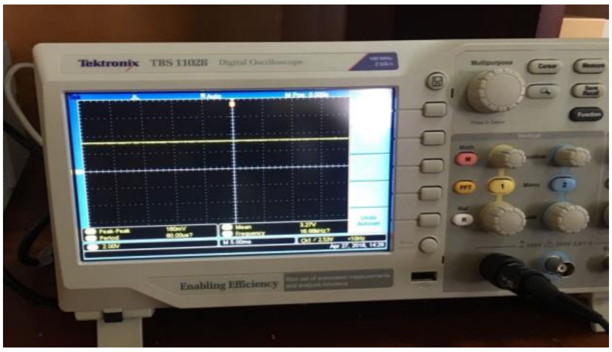

Figure 19 – Error signal when the line is in the right side of the sensor panel

The error signal generating circuit worked properly displaying zero error when the line is in the middle, a positive proportional error when the line is in the right and a negative proportional error when the line is in the left.

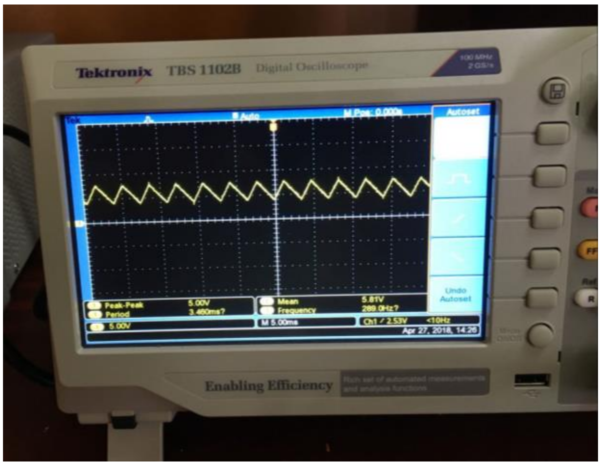

Figure 20 – The triangular waveform

We could obtain a triangular waveform after performing some calibrations and debugging.

4.3 PID Controller and Motor Controller Circuit

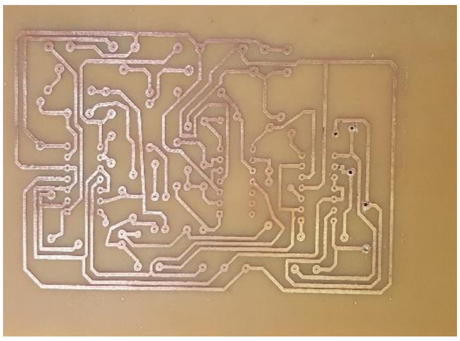

Figure 21 – PCB before soldering

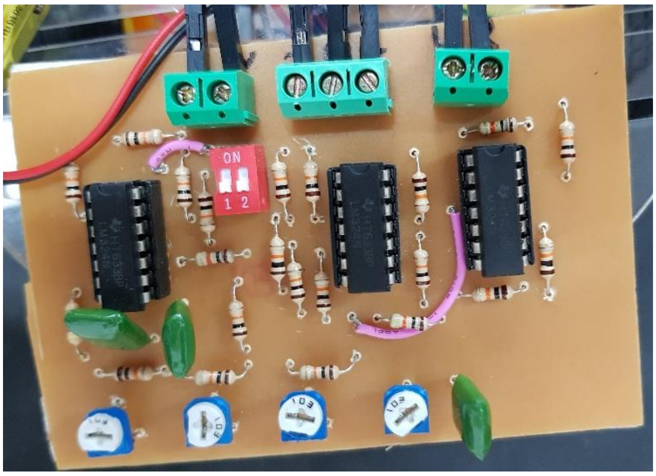

Figure 22 – PCB of PID Control and Motor Control Circuit

The PID controller and motor controller worked fine. We checked the functionality of each small unit using the oscilloscope. We were able to output the two PWM signals for the two motors and the duty cycle of the waveforms changed based on the sensor inputs. We could tune further using the potentiometers. The base speed of the robot was set to the mean of the triangular wave thus we can ensure it has a low probability of having 0 duty cycle or 100 duty cycle PWM signals.

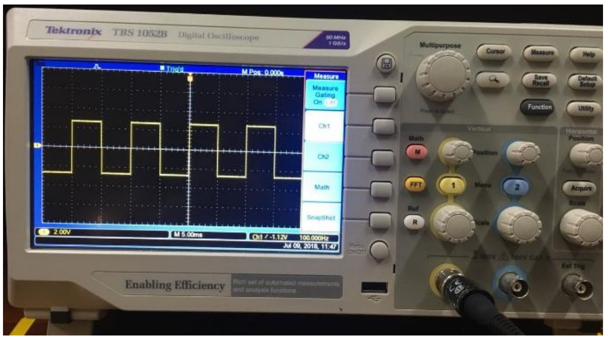

Figure 23 – The left motor PWM signal

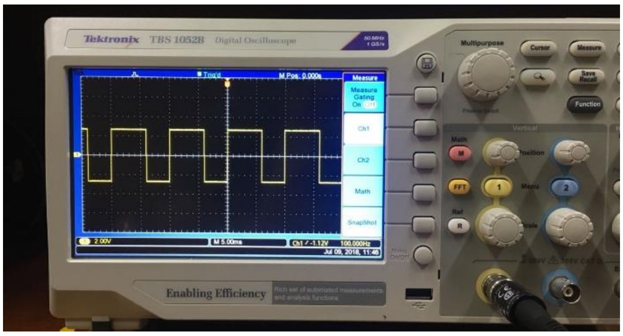

Figure 24 – The right motor PWM signal

4.4 Motor Driver, Stop Condition and Power Supply Circuit

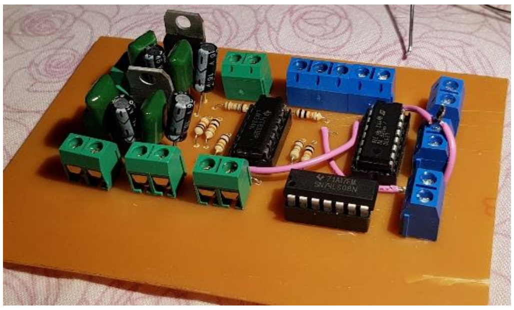

Figure 25 – PCB of the Motor Driver, Stop Condition and Power Supply Circuit

We were able to rotate the motors according to the PWM signals of the previous circuit and the motors stopped when we placed a white line across all the sensors. Power supply unit gave a stable output for 5V and 9V by regulating the Lipo battery voltage. Since we were using a 9V DC battery for generating -9V, we had to replace it after using for few days.

After verifying the operation of each circuit separately we connected all of them and tested again. There were few problems and after correcting them we were able to ensure the functionality of the whole system.

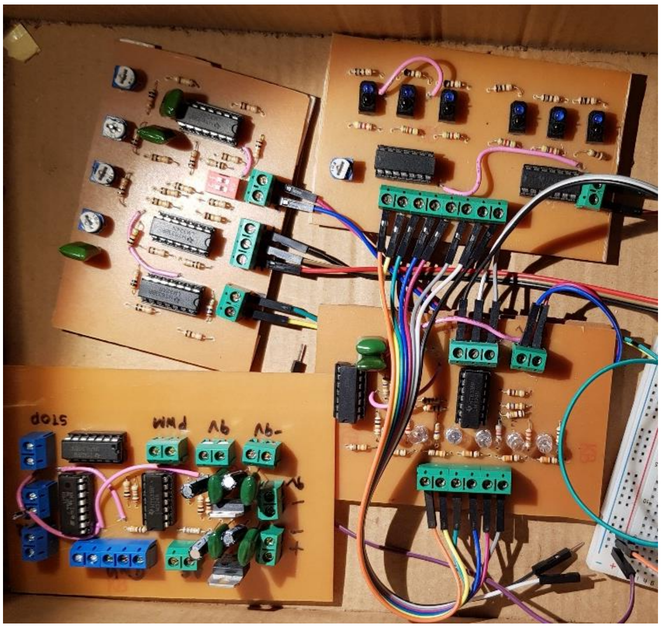

Figure 26 – Four PCBs connected together

Final phase of the project was to assemble all of the components together. It was a time consuming task since our chassis was not custom made. After assembling all the components and connecting them together we checked the whole system again.

After ensuring the proper functionality we placed the robot on a line following maze prepared by ourselves. We had to calibrate the sensor and tune the PID and base speed potentiometers for a better result. After tuning and adjusting few times we could obtain a properly working line following robot. The behaviour of the robot is smooth considering the fact that the whole design is fully analog without using any microcontrollers or algorithms.

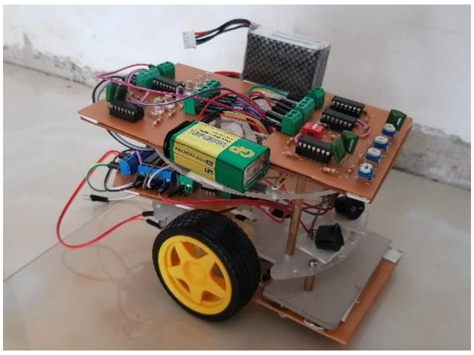

Figure 27 – Assembled Robot

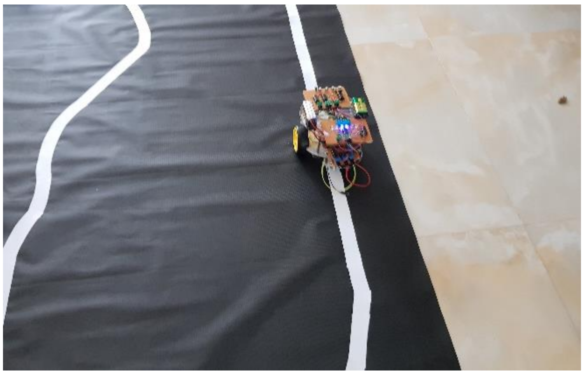

Figure 28 – Analog line follower in action

5. DISCUSSION

Designing an analog line following robot was a new experience for us. Although we were familiar with line followers, implementing the whole thing using analog components only was a challenging task. The first thing was to identify the different circuits required for different operations required. After designing the circuits each circuit was tested in proto boards before printing PCBs.

We followed a step by step approach as in each tested circuit was printed on a copper board and the following circuit was tested on the proto board using that PCB. After printing and debugging all circuits, all components were assembled on the chassis. We had to tune and calibrate the robot several times in order to get a proper output. Finally we were able to come up with a proper analog line following robot with a stopping condition.

We faced few problems and challenges throughout the process. We had to modify our designs few times based on the results taken from the oscilloscope. PID controller was tested for different known signals and the output was observed from all three parts.

One issue with the robot is the 9V battery which we used for supplying negative voltages. We had to replace it few times. Another issue is the necessity of tuning the robot before each run depending on the surface conditions and ambient light conditions. Although we can't modify the behaviour using a code or an algorithm we could do significant changes using the potentiometers we used for IR sensors, PID control and base speed.

6. ACKNOWLEDGMENTS

First we would like to pay our gratitude to Dr. Jayathu Samarawickrama and Eng. Kithsiri Samarasinghe for providing us with the theoretical knowledge about Op Amps and their applications. We are grateful to our supervisor Mr. Didula Dissanayaka who helped and guided us throughout the project.

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We take this opportunity to thank all the instructors, lab assistants, senior students, batch mates and all other personals who helped us in many ways to make this project a success. Your contribution is highly appreciated.

7. REFERENCES

1. http://www.will-moore.com/analog-line-follower

(analog line follower project by Will Moore)

2. http://www.ermicro.com/blog/?p=1908 (LM324 analog line follower project using LDR sensors)

3. https://www.electronics-tutorials.ws/opamp/opamp_4.html (Basic Op Amp Circuits)

4. http://www.ecircuitcenter.com/Circuits/op_pid/op_pid.htm (Analog PID controller)

7. APENDICES

7.1 Appendix I - Schematic Designs

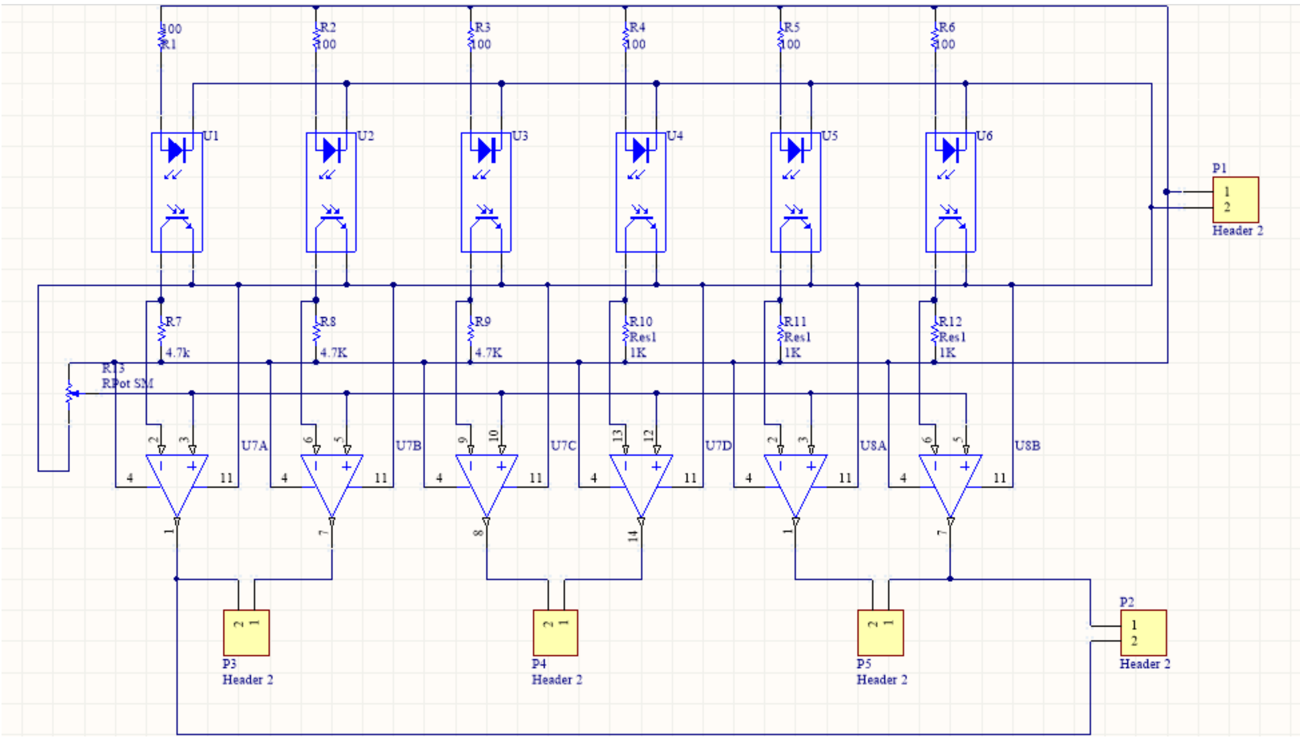

Figure 29 – Sensor Panel Circuit Schematic

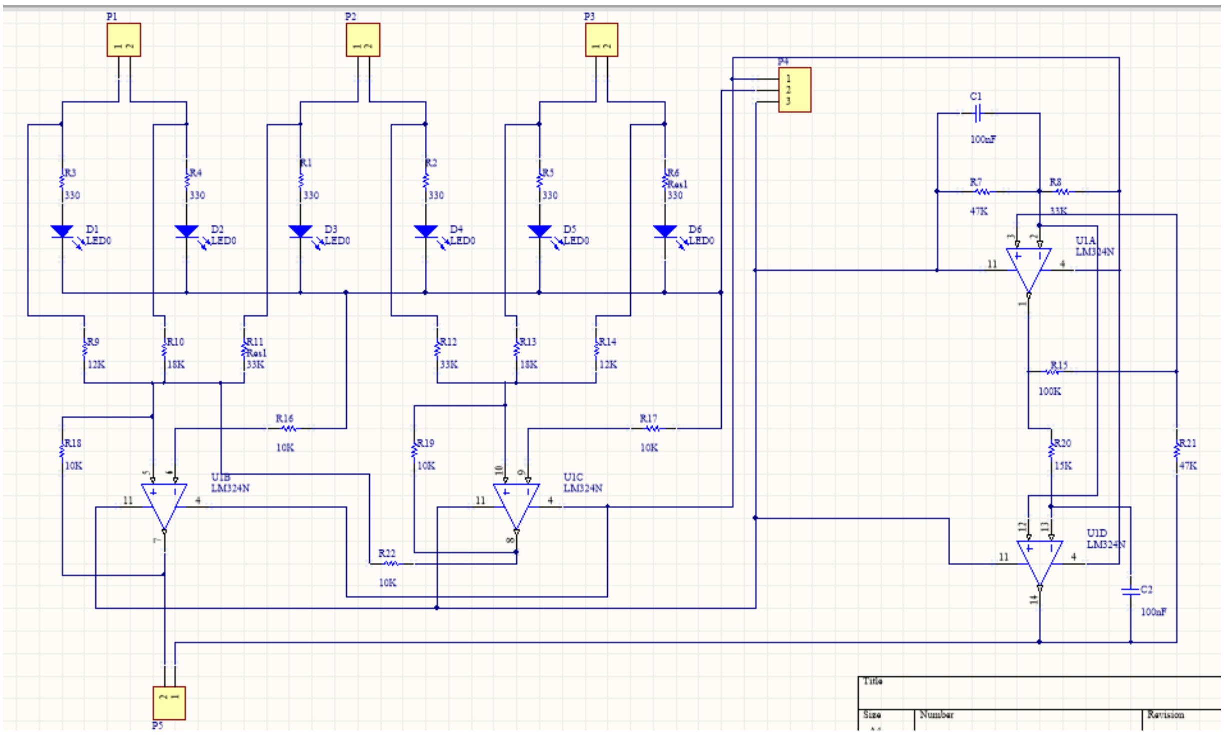

Figure 30 – Error and Triangular Wave Circuit Schematic

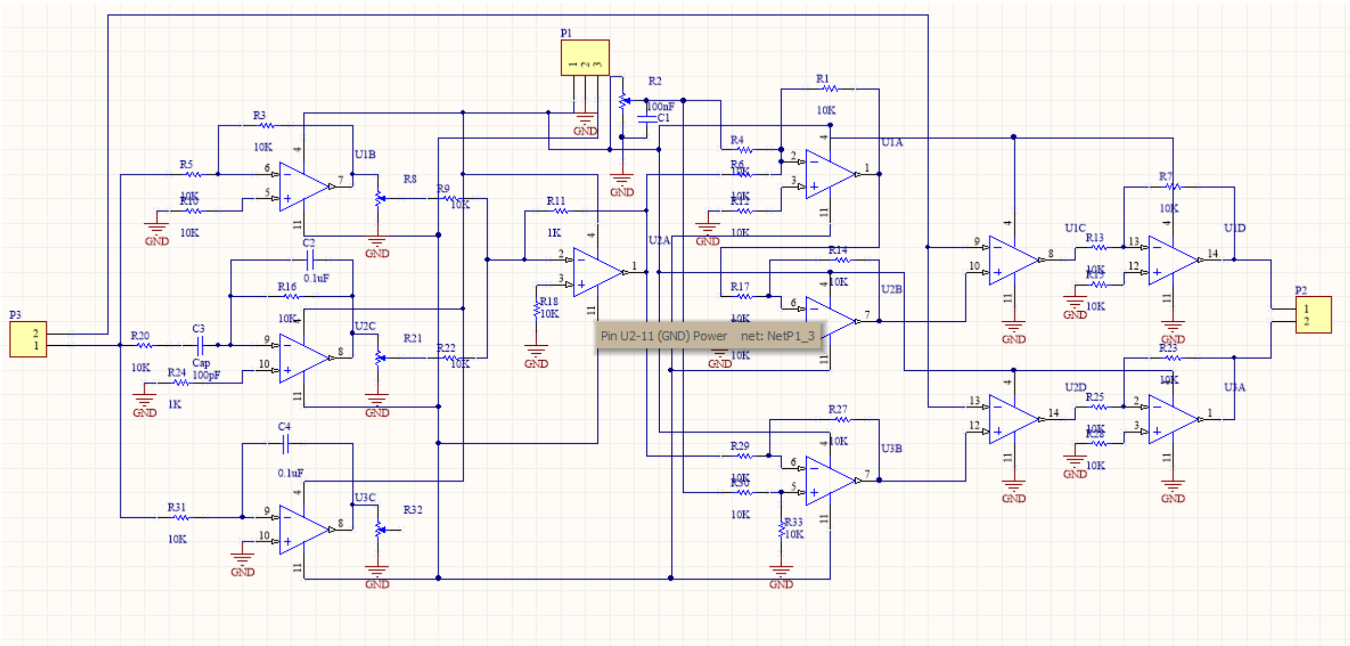

Figure 31 – PID Control and Motor Control Circuit Schematic

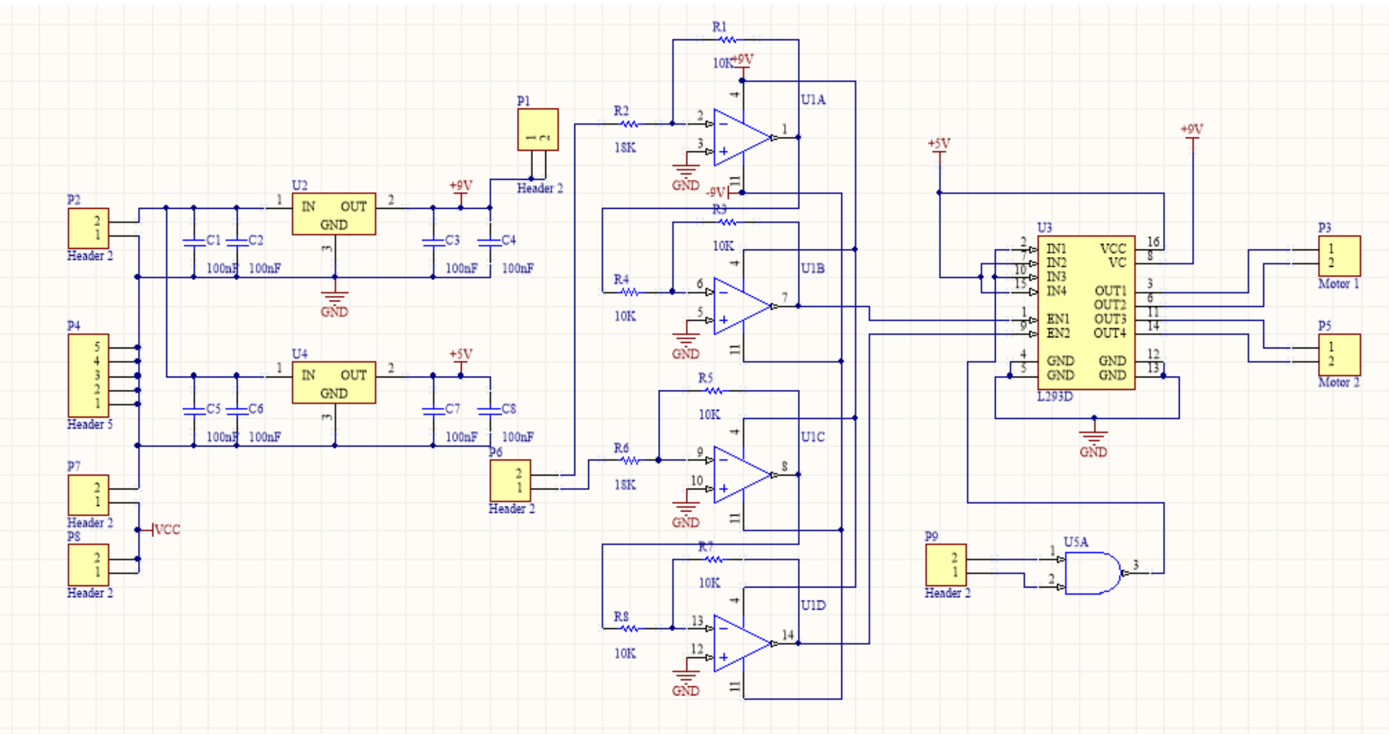

Figure 32 – Power Supply, Motor Driver and Stop Circuit Schematic

7.2 Appendix II – PCB Layout

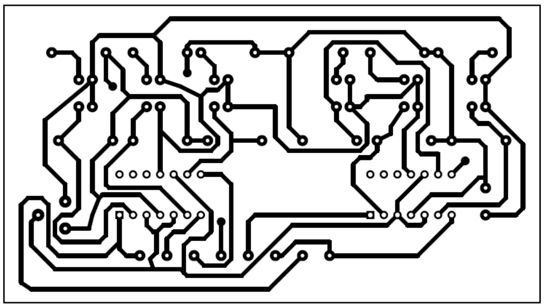

Figure 33 – Sensor Panel Circuit PCB Layout

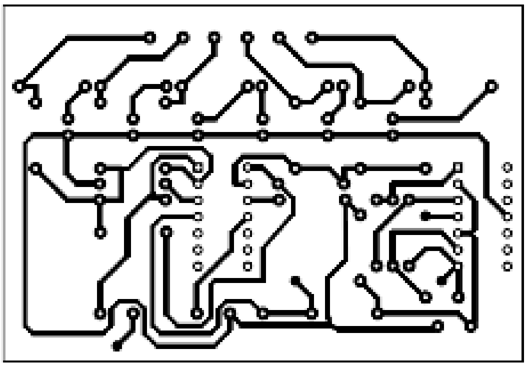

Figure 34 – Error and Triangular Wave Circuit PCB Layout

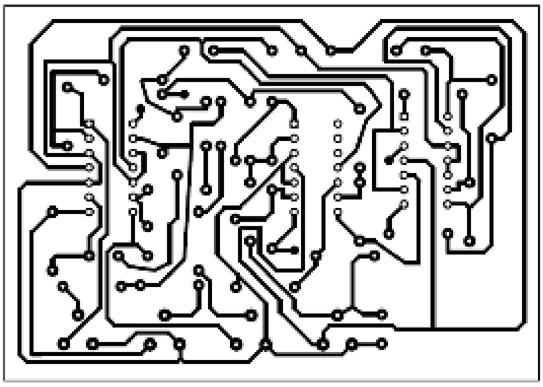

Figure 35 – PID Control and Motor Control Circuit PCB Layout

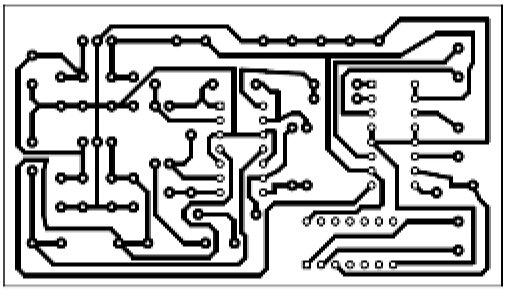

Figure 36 – Power Supply, Motor Driver and Stop Circuit PCB Layout