Heriot-Watt University Dubai

B37VR Robotics Group Project, Year 1

IR Sensor Characterisation Report

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Abstract

IR sensors are the eyes of an autonomous line following robot. The sensor's characteristics must be understood to find the right thresholds of what the robot considers a line to follow. The experiments aimed to investigate IR sensor readings on different types of surfaces – grey floor, clean black tape and dirty black tape - and under different lighting conditions. An Arduino program was used to read the three IR sensor's values. The results found that black tape, whether clean or dirty, produce a higher IR sensor reading than the grey floor. Increased ambient lighting increased the sensor reading in the grey floor, however this wasn't observed in all surfaces, due to uncontrolled ambient lighting. The line following threshold values were found – the line is detected on values above 674. However, with the limited setup, the effects of ambient light and distance couldn't be found.

Contents

Introduction

IR sensors are a core component of an autonomous line following robot. It serves as the ‘eyes’ of the robot, determining where the line is, and sends the recorded data to the Arduino Uno microcontroller which computes and updates the direction of the buggy. The TCRT5000 sensor used in this experiment is a reflective sensor which includes an infrared emitter and a phototransistor [1], and detects black lines by determining the amount of light which is reflected back (black absorbing more light than other surfaces).

In order to detect lines, a threshold of what is a black surface must be determined. This lab report aims to characterise the TCRT5000 sensor to determine the analog read values of different surfaces to define the sensing threshold of the black line to be followed and to analyse how the sensor’s readings are affected by different variables such as ambient light, the quality and texture of the surface. By the end of these series of experiments, the sensor’s characteristics will be determined and understood and the appropriate line reading threshold will be found.

Objectives:

- Understand the working principle of the TCRT5000 IR sensor.
- Test different surfaces against the IR sensor and find the right threshold for line following.
- Evaluate the effects of ambient lighting on the accuracy of the IR sensor.

Background Theory - How IR sensors work and how it can detect lines

As briefly mentioned in the introduction, the TCRT5000 sensor is a reflective optical sensor with a transistor output, including an infrared emitter and a phototransistor [1].

The diagram below *(Figure 2.1)* is the circuit schematic of the sensor and how its used to read values.

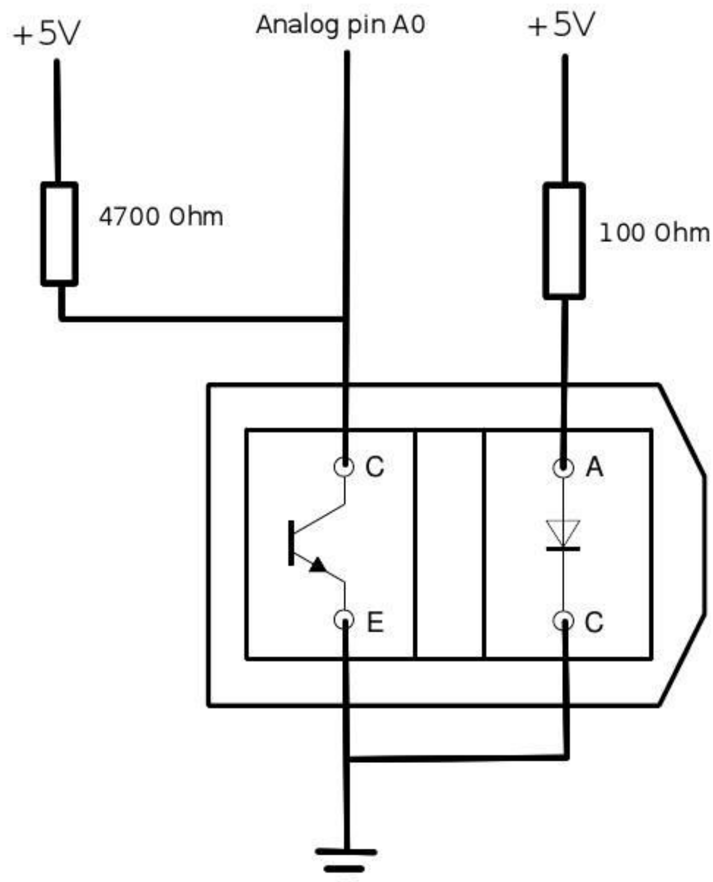


Figure 2.1: Top-down schematic view of the IR sensor, and how its connected to the Arduino analog pin A0 to read the sensor. [2]

Figure 2.2: The TCRT5000 sensor. The black wall between the phototransistor and the IR LED blocks the emissions directly from the LED so that it can only detect the waves reflected back by surfaces. Image from the data sheet [1].

Essentially, the LED between points A and C shown on the figure above is an Infrared LED which emits a wave of 950nm [1]. The wave is emitted and is reflected on a surface, back to the sensor. The phototransistor detects the reflected infrared light – when light falls on the transistor, the atoms in the collector region become excited and emit free electrons [3], allowing current to flow through from the collector to the emitter. Therefore, as more light is detected, more atoms get excited and more electrons are freed, allowing more conductivity. This will cause more current to flow to the ground. This reduces the output voltage at point C, producing lower values.

In summary:

- IR LED emits light
- Light reflected and sensed by the phototransistor
- When the transistor detects light – more current flows to ground, less current flows to analog pin
- Therefore, more light = smaller reading; less light = greater reading.

Methodology

In this lab report, various experiments were taken to characterise the IR sensor under different operating conditions - types of surfaces, and how the sensor reacts to different environmental ambient lighting. With the results gathered from these experiments, the line following threshold can be found.

Experimental setup

The following experiments were done using the Robotics Group Project buggy *(Figure 3.1)* provided by the course. It includes an Arduino Uno microcontroller, a breadboard for connections, an H-Bridge motor driver and a pair of motors (not used in this experiment), and a line following module – a PCB consisting of three TCRT5000 sensors, which are going to be characterised in these experiments.

The following connections were made *(as shown on figure 3.2)*. 5V connected to the +5V pin on the Line Follower, channel 1, 2 and 3 connected to analog pins A3, A4 and A5 respectively and GND connected to GND. The fully wired IR sensor reading setup is shown on *figure 3.3* below.

Figure 3.1: Arduino buggy used in this experiment. Other connections and modules were connected to the Arduino for other functionalities in the line following buggy – these can be ignored.

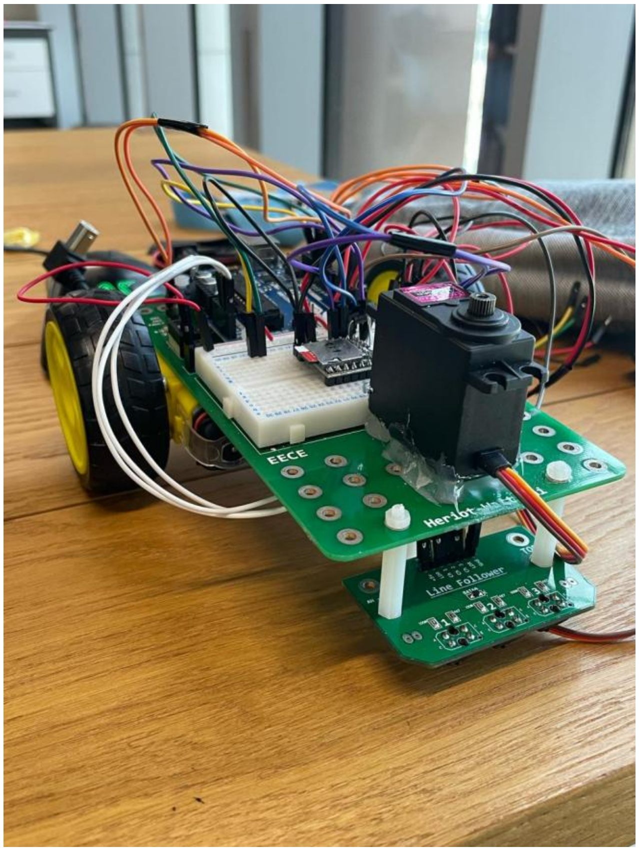


Figure 3.2: Schematic diagram of the IR sensor reading experimental setup.

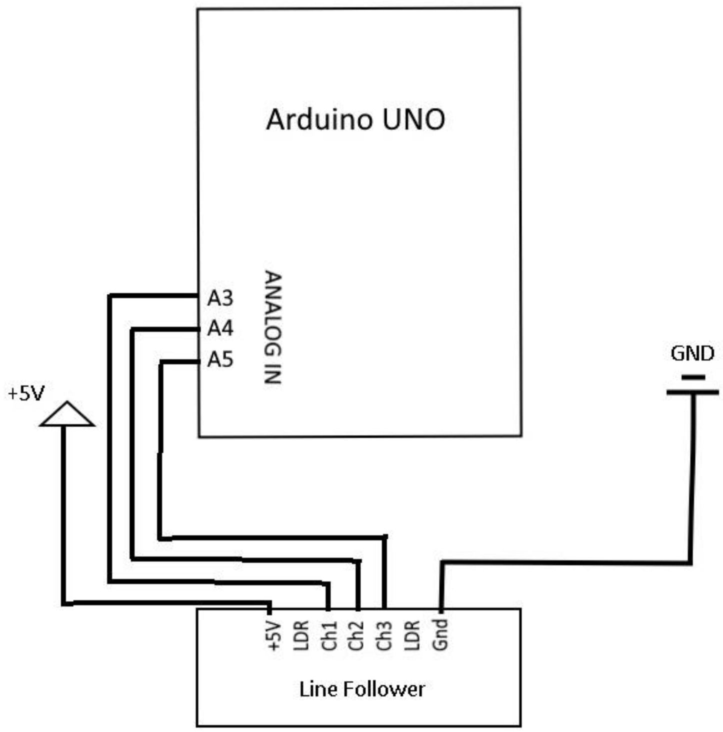
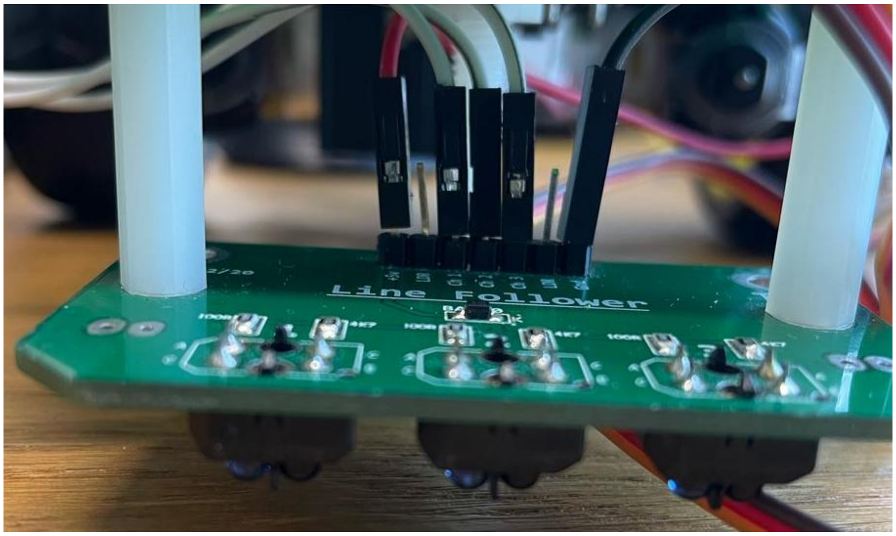
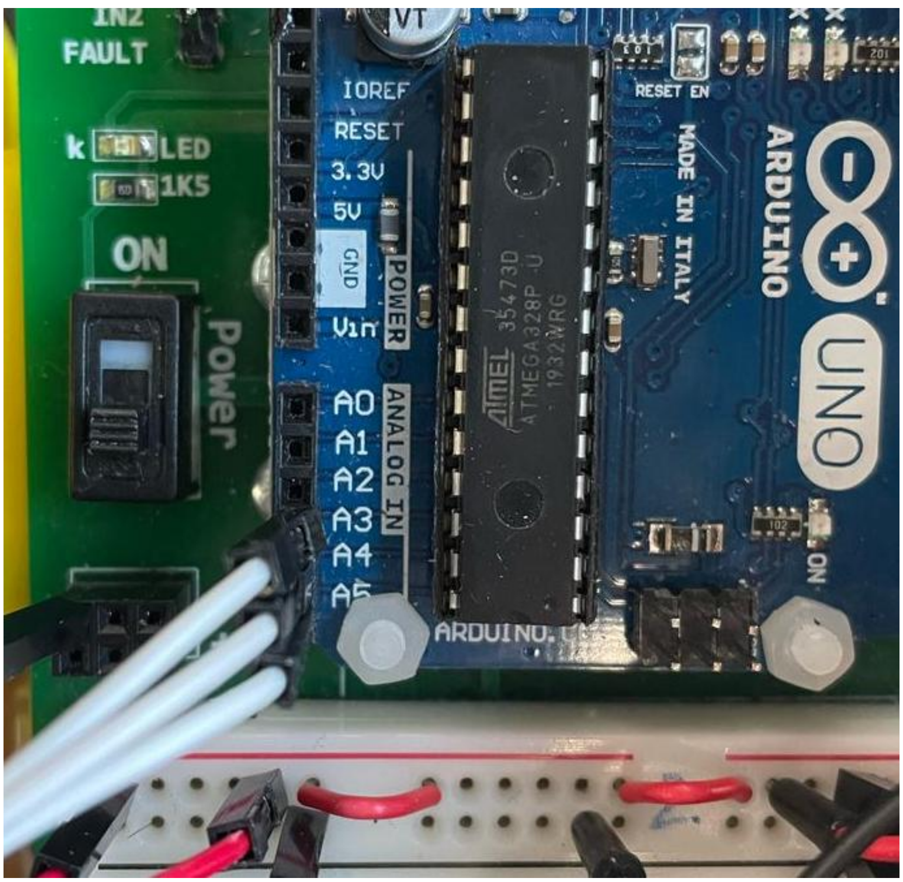


Figure 3.3: The fully wired Arduino buggy, labelled. The connections in the breadboard and additional pins can be ignored as they are used for the completed project.



A – Connections in the Line Follower Module – Power and GND connected, and channels connected to A3, A4 and A5.



B – Connections to the Arduino – A3, A4 and A5 are connected to the left, middle and right channel of the Line Follower Module.

The Line Follower PCB

As previously mentioned, the three TCRT5000 sensors are soldered onto a PCB. The schematic diagram of the Line Follower module is attached on Appendix A. In summary, channel 1, 2 and 3 is connected to the collector pins of the left, centre and right sensors, and these are connected to the Arduino Uno's A3, A4 and A5 analog pins.

Arduino code – IRSensorRead.ino

The sketch *IRSensorRead.ino* (full code available on Appendix B) is uploaded onto the Arduino Uno. It reads each channel's analog output using analogRead(), an inbuilt function which reads the voltage in the analog pins as a value between 0-1023 bits. To convert this value into voltage, the following equation can be used:

$$V = \frac{Analog\ read\ value + 1}{1024} \times 5$$

The program outputs the values in the format <left value>,<middle value>,<right value> on the Serial Monitor, which can be easily copied and pasted into a .csv file, which can later be opened in Excel for data analysis.

Surfaces

Figure 3.4: The different surfaces that will be tested in the experiments.

Type of Surface	Reason
Grey floor of robotics lab	Line following buggy demonstration will be carried out on the floor of the Robotics lab.
Glossy black electrical tape	Line following buggy designed to follow standard glossy black electrical tape on the floor of the Robotics lab.
Dirty dull black electrical tape	To test the tolerances the threshold should include. There may be imperfections in the line, so a dirty dulled out black electrical tape can serve as an extreme corner case for imperfections.

Figures 3.5 – 3.7 are pictures of the surfaces measured in this experiment.

Figure 3.5: Grey floor of the Robotics Laboratory

Figure 3.6: Clean black tape

Figure 3.7: Dirty black tape

For the setup used in the experiments, strips of tape were placed on the ground.

<u>Ambient lighting</u>

To measure the IR sensors' readings, the environment had to be as controlled as possible – the background lighting of a room interferes with the IR sensor readings. The ambient light had to be controlled as much as possible. Ideally, a totally dark environment should be used to eliminate the variable of ambient lighting. However, there were no totally dark areas in university where the experiment could be done, so two different light settings were chosen – dim and bright.

In previous experiments, the light intensity was measured with a luxmeter [4], and the correlation between light intensity and accuracy was found. However, due to limited resources, no light intensities could be quantified.

Lighting	Description
Dim	All lights in the Robotics Lab were dimmed to the lowest possible setting. Blinds and curtains were fully closed. The experiment was set up in a place far away from windows and other potential light sources.
Bright	All lights in the lab were set to the brightest setting. Blinds and curtains were fully drawn open to let as much sunlight in. However, the experiment was done in the same place so that the surfaces will be the same.

Figure 3.5: Two different lighting conditions that were controlled.

<u>*Distance*</u>

Initially, the effect of height on the IR sensor's readings were to be investigated to find the optimal distance of the IR sensor from the ground for line following. Previous experiments [4] on IR sensor characteristics have done this using a custom-made jig, to measure the effects of distance to accuracy and precision. However, with the limited resources available, there were no ways to change the height accurately. In previous attempts, soldering helping hands were used to suspend the sensor and change the heights, but there was no proper way to repeat heights for experiments as there was a lot of human error – the angle, positioning, different heights, etc.

For this experiment, height was kept constant by attaching the Light Follower module to the buggy. This will be the same height used for line following, so it was practical.

Procedure

The experiment was first setup as described above – Code uploaded onto the Arduino, connections between the analog pins and the Line Follower module's channels were made, surfaces were laid out, and ambient lighting were set.

The first experiment's goal was to determine the IR sensors' readings on each surface in the controlled dim light environment.

1) The readings for the floor were tested. The program was allowed to loop until approximately 20 sets of values were on the Serial Monitor in Arduino IDE.
2) These values were copied and recorded onto a CSV file.
3) This is repeated for the different surfaces – the clean glossy black electrical tape, and the dull dirty black electrical tape.

The second experiment's goal was to investigate the effects of ambient room lighting on the IR sensors' readings. The first experiment was repeated, but this time, instead of having the room's lights dimmed, the lights were maximised to the brightest setting, and the windows were drawn open.

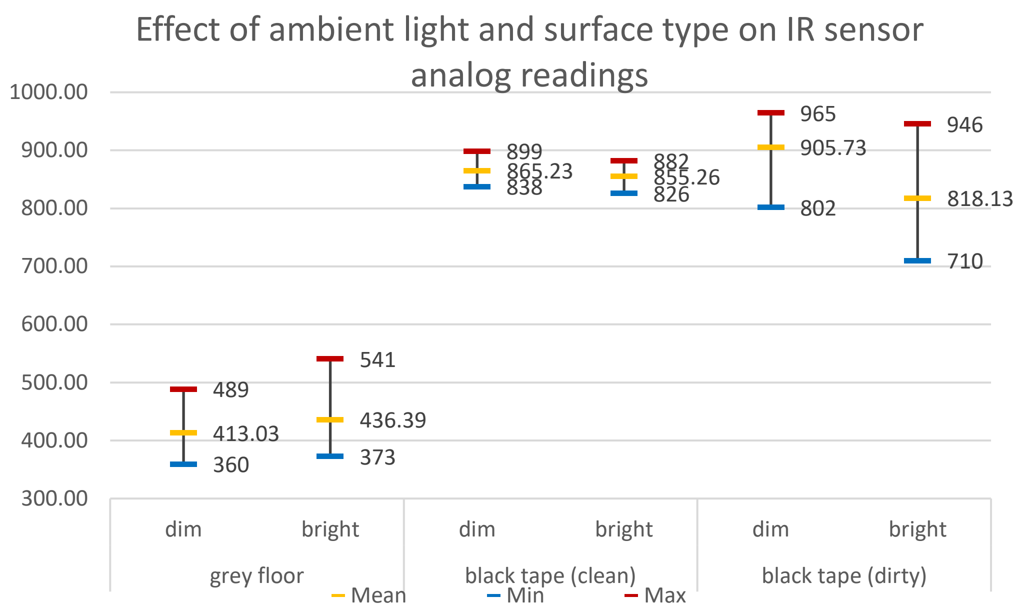
Results

This section of the report presents the results of the IR sensor characterisation experiments, showing the effects of surface type and ambient light on the three sensors' readings. The collected data *(raw data available on Appendix C)* includes the type of surface, the ambient lighting of the room, the average analog pin readings from the sensor, the average voltage, the minimum and maximum readings and standard deviation. The key findings are summarised in figures 4.1 to 4.4 below.

Figure 4.1: *The effects of ambient lighting and surface type on IR sensor readings*

Ambient Lighting	Surface type	Mean analog pin reading	Minimum analog pin reading	Maximum analog pin reading	Range
dim	Grey floor	413.03	360.00	489.00	129
dim	Black tape (clean)	865.23	838.00	899.00	81
dim	Black tape (dirty)	905.73	802.00	965.00	163
bright	Grey floor	436.39	373.00	541.00	168
bright	Black tape (clean)	855.26	826.00	882.00	56
bright	Black tape (dirty)	818.13	710.00	946.00	236

Figure 4.2: *A minimum-maximum chart comparing the effects of lighting and surface on the IR sensor readings.*

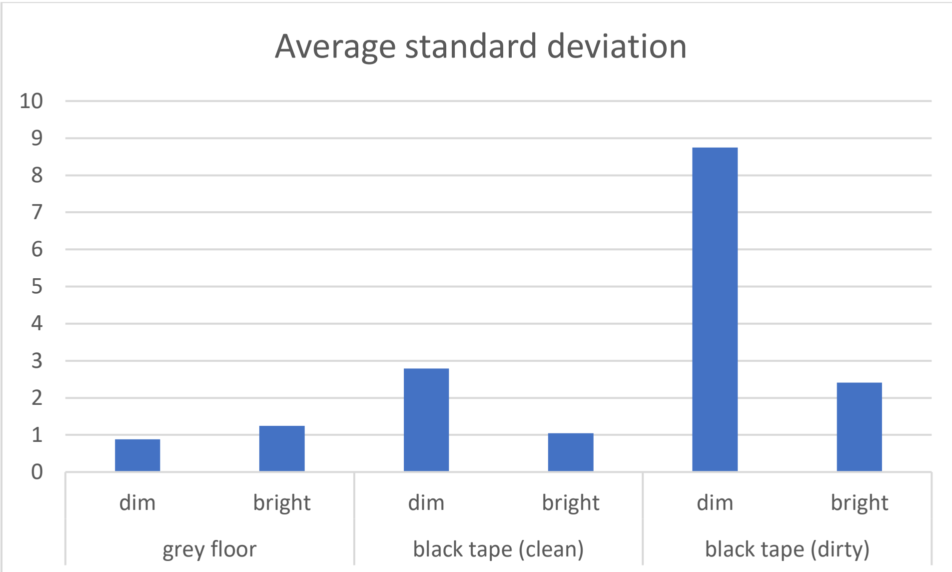


The standard deviation of the analog readings provides a measure of the IR sensor's precision under different working conditions.

Figure 4.3: *The average standard deviation of analog readings depending on the lighting and surface conditions.*

Lighting	*Surface*	*Average standard deviation*	*Range*
dim	grey	0.88	129
dim	clean	2.79	81
dim	dirty	8.75	163
bright	grey	1.24	168
bright	clean	1.05	56
bright	dirty	2.41	236

Figure 4.4: *The average standard deviations, graphed.*



Discussion

This study investigated the effects of ambient background lighting and surface conditions on IR sensor readings. The results show that the sensor readings varied significantly based on the different factors – ambient lighting and surface type.

The results support the initial hypothesis - both clean and dirty black tape yielded higher readings than the floor as they reflect less light back. For example, when under dim light conditions, the floor returned an average reading of 413.03, compared to the higher readings of clean (865.23) and dirty black tape (905.73). Surface colour does affect the amount of infrared radiation absorbed as previously hypothesised, however, the type of surface – the reflectivity and smoothness – should also be accounted for. The black tape has a glossy finish which makes it act essentially as a mirror. Mirror reflection occurs when light strikes surfaces that are smooth or glossy, like the glossy black tape, reflecting at the opposite direction from the source [5]. Though the tape was glossy, because it was black, more infrared light was absorbed, hence giving a higher reading.

The uniformity and texture of the surface influences the IR sensor readings. The sensor readings were different when testing out clean and dirty tape surfaces. Under dim light conditions, the clean tape produced an average reading of 865.23, whereas the dirtier tape returned an average reading of 905.73. This is because the different dust and dirt particles in the dirty tape creates an uneven surface with different heights and colours, causing light to reflect in different directions, therefore less light is detected by the sensor.

The dirtier tape provided a greater range of readings, proving the influence surface texture has on sensor precision and accuracy. The clean tape has an average standard deviation of 2.76, while the dirty black tape has an average standard deviation 8.75, meaning that it read a wider range of values. As previously mentioned, this is because of the uneven surface with different heights, colours and reflectivity because of dust and dirt particles, reflecting light in different directions, which gives a wider range of values.

Different ambient light conditions affect sensor readings. For the grey floor, brighter room conditions increased the sensor readings compared to the dimmer room. Under dim light, the sensor read 413.03 on average, and under brighter light, the sensor read 436.39. Hypothetically, the reading should be lower because the IR sensor would detect more light from the environment, but that isn't the case. This can be an anomalous reading. For the other surfaces, the results were as expected – for the clean black tape, it read 865.23 in dim light decreasing to 855.26 in bright light. This is because more IR light is detected from the surroundings, hence the lower reading. This is similar for the dirty tape (905.73 in dim, 818.13 in bright).

Interestingly, brighter room conditions increased the precision of reading black tape readings. Under dim light, the clean and dirty tape, had average standard deviations of the clean and dirty black tape were 2.79 and 8.75 respectively. Comparatively, under bright light, the clean and dirty tape, on average, had standard deviations of 1.05 and 2.41. The inconsistencies of the readings could be because the ambient lighting in the room couldn't be perfectly controlled – non-uniform lighting, large windows on two sides of the room, position of the sun in the experiment, shadows, flickering room lights, etc. Therefore, the results fail to establish a relationship between ambient light and the precision and readings of the IR sensors – showing the importance of having a controlled laboratory environment for future iterations of this experiment.

For future experiments to investigate the effect of ambient light, a luxmeter should be used to measure the actual lighting on the room and find a correlation between the ambient lighting and sensor noise. A controlled environment where the lighting can be controlled should be used. To test the IR sensors without ambient light interference, the experiment must be done in a dark room.

Using the results, the global minimum and maximum thresholds for detecting surfaces can be finally determined. This is displayed on figure 5.1.

Figure 5.1: The line following thresholds.

Surface	Min	Max	Min -5%	Max+5%
Floor	360.00	541.00	342	568
Line	710.00	965.00	674	1013

Conclusion

The aim of this lab report was to characterise a set of IR sensors to calibrate it and find an appropriate threshold for line detection for the line following buggy. The experiments and research carried out in this study successfully provided insight on the working principles of how IR sensors can be used to detect lines for an autonomous line following robot. The experiments aimed to investigate the influence of surfaces and ambient lighting on IR sensor readings, and it concluded that darker surfaces reflect less light, producing a greater IR sensor reading. With the limited experimental setup, the effects of ambient lighting on the IR sensor's precision couldn't be properly investigated as the room's lighting couldn't be quantified.

The ideal line detection thresholds have been successfully found in this experiment. This can be applied to the line following code to ensure precise line detection.

For future iterations of this study, a controlled environment where the ambient lighting can be measured and tweaked should be used to mitigate the errors caused by uncontrolled ambient light. Additionally, conducting the test in a fully darkened room can stop the ambient IR interference, or enclose it in a box. A lux meter should be used to measure the light intensity of ambient light.

Studying the effects of distance and angle from the surface can provide further insight to how it affects IR sensor readings, and using the results from the testing can give the ideal sensor position for line following, sensor sensitivity, noise and precision.

Now that the IR sensors were characterised, it can be used to make an autonomous line following robot.

References

[1] Vishay Semiconductors (2009). *TCRT5000, TCRT5000L Data sheet - Reflective Optical Sensor with Transistor Output.* [Component data sheet] [Online] Available at: https://www.vishay.com/docs/83760/tcrt5000.pdf (Accessed at: 7th March 2025).

[2] B37VR Robotics Group Project (2025). *TCRT5000 connection diagram - tcrt5000-connection.jpg.* [Canvas] Available at: tcrt5000-connection.jpg. (Accessed at: 7th March 2025).

[3] Bishop, O. (2001) 'Optoelectric Sensors', in *Understand Electronics*. Newnes, pp. 131–137.

[4] B. Azzopardi, E. Dimech, A. Sammut and A. Mifsud (2023). "Characterisation of Infrared Sensors for Close-Proximity Distance Measurement," *IECON 2023- 49th Annual Conference of the IEEE Industrial Electronics Society*, Singapore, Singapore. pp. 1-6. Available at: doi 10.1109/IECON51785.2023.10312588. (Accessed at 11th Match 2025)

[4] 3M (2004) *Reflectivity flyer*, [Flyer] [Online PDF] Available at: https://multimedia.3m.com/mws/media/295767O/reflectivity-flyer.pdf. (Accessed at: 13th March 2025).

Appendix

Appendix A – Line Follower PCB circuit diagram

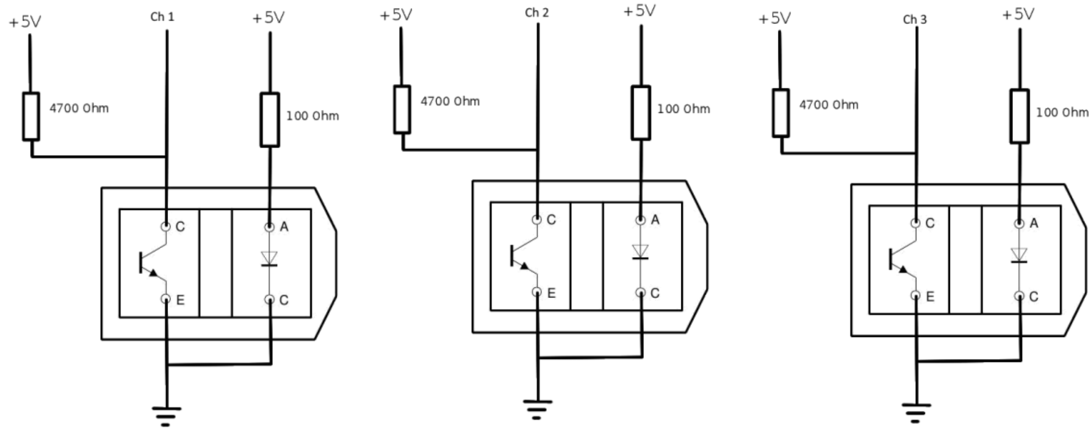


Figure A.1: Line Follower PCB circuit diagram. Consists of three IR sensors next to each other, and has pins Ch 1, Ch 2 and Ch 3 which are connected to the Arduino.

Appendix B – IRSensorRead.ino

The code below is a modified version of the sketchIRsensorRead.txt code taken from Canvas – changing it so that the printed values are in a .csv format for ease of data analysis in Excel.

```
/*
Read 3 IR sensors for callibration
*/
// Read 3 IR sensors for callibration
//
/*
  AnalogReadSerial

  Reads an analog input on pin 3,4 &5, prints the result to the Serial Monitor.
  Graphical representation is available using Serial Plotter (Tools > Serial
Plotter menu).

  Adapted from the example code is in the public domain.

  http://www.arduino.cc/en/Tutorial/AnalogReadSerial
*/

// the setup routine runs once when you press reset:
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
}
```

```
// the loop routine runs over and over again forever:
void loop() {
  // read the input on analog pin 0:
  int sensorValueLeft = analogRead(A5);
  delay(2);
   int sensorValueCentre = analogRead(A4);
  delay(2);
   int sensorValueRight = analogRead(A3);
  delay(2);
  // print out the value you read:
  Serial.print("");
  Serial.print(sensorValueLeft);
   Serial.print(",");
  Serial.print(sensorValueCentre);
   Serial.print(",");
  Serial.println(sensorValueRight);
  delay(1000);        // delay in between reads
}
```

Appendix C: Raw data summary

Sensor Position	Lighting	Surface	Average analog reading	Standard deviation	Voltage (average)	Min	Max
left	dim	Grey floor	362.00	0.97	1.77	360.00	365.00
		Clean black tape	846.56	2.85	4.13	838.00	852.00
		Dirty black tape	833.70	8.81	4.07	802.00	840.00
	bright	Grey floor	374.90	1.58	1.83	373.00	382.00
		Clean black tape	828.72	1.05	4.05	826.00	831.00
		Dirty black tape	795.63	3.22	3.88	784.00	799.00
middle	dim	Grey floor	390.00	0.89	1.90	389.00	393.00
		Clean black tape	855.48	2.82	4.18	847.00	861.00
		Dirty black tape	925.07	8.68	4.52	895.00	931.00
	bright	Grey floor	396.30	1.13	1.94	395.00	400.00
		Clean black tape	858.24	0.82	4.19	857.00	860.00
		Dirty black tape	715.43	1.84	3.49	710.00	717.00
Right	dim	Grey floor	487.10	0.79	2.38	486.00	489.00
		Clean black tape	893.607	2.69	4.36	885.00	899.00
		Dirty black tape	958.43	8.74	4.68	928.00	965.00
	bright	Grey floor	537.97	1.02	2.63	537.00	541.00
		Clean black tape	878.83	1.29	4.29	874.00	882.00
		Dirty black tape	943.33	2.17	4.61	936.00	946.00