Final Report

Micro-mouse Sensor Subsystem

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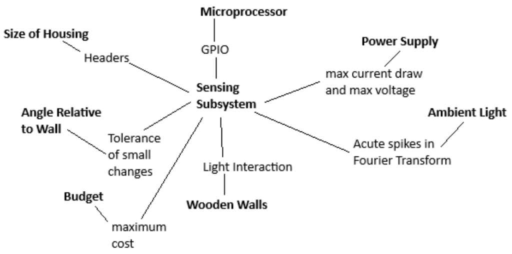


Figure 1.1: Context Diagram for Sensing Subsystem

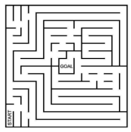


Figure 1.2: Typical Maze for Micro-mouse

Chapter 1

Introduction

1.1 Problem Description

This report concerns the sensing subsystem of a micro-mouse robot that can navigate and solve a maze, which is a competitive engineering challenge with global competitions. It hinges on smart algorithms and fast hardware. This subsystem must interface with an already existing motherboard (having a microprocessor and power subsystem) and housing. A context diagram and example of the type of maze that will be used for testing are shown in Figure 1.1 and Figure 1.2 respectively. The sensor must use infrared light to sense wooden maze walls around it so that the microprocessor can make decisions on how to navigate and solve the maze using two motors attached to the housing.

1.2 Scope and Limitations

The sensor has two functions that must be designed for, using the peripherals of the microprocessor on the micro-mouse:

1. Radiate infrared light to the environment such that the intensity of the light is high enough that it will be reflected with enough energy to be detected, but low enough to not over-saturate the subsystem receiver.

2. Convert reflected infrared light into voltages that can be used by the GPIO peripherals of the microprocessor to create a high-enough resolution map of the environment to navigate the maze.

This must be done within a defined budget and should be made energy-efficient. At this level, how the sensing data will be used is unknown.

1.3 GitHub Link

Click here to view the Github repository for this report.

Chapter 2

Requirements Analysis

2.1 Requirements

The requirements for a micro-mouse sensing module are described in Table 2.1.

Table 2.1: User and functional requirements of the power subsystem.

Requirement ID	Description
R01	Detect whether there is a wall in front and on the sides of robot
R02	Have switching means to save power when not in operation
R03	System must be reliable
R04	Must not drain the battery too quickly such that the micro-mouse cannot finish maze
R05	Cost of solution must fall within budget (business requirement)
R06	PCB must not be to large
R07	Must not be severely affected by ambient light

2.2 Specifications

The specifications, refined from the requirements in Table 2.1, for the micro-mouse sensing module are described in Table 2.2.

Table 2.2: Specifications of the sensing subsystem derived from the requirements in Table 2.1.

Specification ID	Description
SP01	Must have 2x14 (2.54mm pin pitch) connection pinouts to connect to motherboard.
SP02	Must not be more than 115mm width of motherboard to avoid. knocking walls.
SP03	Must not take any space behind the pinout to avoid interfering with other hardware. on the micro-mouse.
SP04	Must not be longer than 45mm to avoid reducing micro-mouse turning radius.
SP05	Keep maximum discharge at 0.5C, implying a maximum current draw of 400mA. from full to fully discharge in two hours.
SP06	Complete PCB manufacture must not exceed. $30 (business specification) pins.
SP08	Sensor output voltage range must be at least 0.5V between 60mm and 180mm away from wall, and does not experience voltage changes from 180mm from wall.
SP09	Sensor must experience at most 50mV difference when rotated 15 and -15 degrees relative to wall.
SP10	Sensor must not experience larger than 1mV output voltage changes when slightly jiggled.
SP11	Use the PWM peripheral circuitry in the microcontroller to toggle when the sensor radiates infrared light.

2.3 Testing Procedures

A summary of the testing procedures is given in Table 2.3.

Table 2.3: Summary of testing procedures

Acceptance Test ID	Description
AT01	Verify that PCB properly connects to motherboard pins and fits onto motherboard without mechanically interfering with other systems.
AT02	Verify that PCB size does not dramatically reduce turning radius of micro-mouse.
AT03	Verify that input current and voltage are not too high.
AT04	Verify that output voltage is appropriate at given distances.
AT05	Verify that output voltage does not vary drastically when rotated through small angles.
AT06	Verify that output voltage does not vary drastically when slightly jiggled.
AT07	Verify that sensor turns on and off based on microcontroller PWM pin.
AT08	Verify that cost of PCB manufacture is below $30.
AT09	Verify that all components are present and placed properly
AT10	Verify that all traces are present and conducting

2.4 Traceability Analysis

The show how the requirements, specifications and testing procedures all link, Table 2.4 is provided.

Table 2.4: Requirements Traceability Matrix

#	Requirements	Specifications	Acceptance Test
1	R01	SP08	AT04, AT09, AT10
2	R02	SP11	AT07
3	R03	SP10,SP09	AT05, AT06
4	R04	SP07,SP05	AT03
5	R05	SP06	AT08
6	R06	SP01,SP02,SP03,SP04	AT01,AT02

2.4.1 Traceability Analysis 1

R01 concerns how well each transmitter-receiver pair can measure distance, which is consistent with SP08. AT04 unit tests each pair to ensure they are consistent with SP08. AT09 and AT10 test whether the board can work at all.

2.4.2 Traceability Analysis 2

R02 requires a way to toggle the infrared emitter functionality of the sensor, which is solved by SP11. AT07 ensures that the sensor integrates with the PWM peripheral of the microcontroller.

2.4.3 Traceability Analysis 3

R03 can be approximated by SP10 and SP09, which outline non-ideal conditions in which the sensor may operate in. AT05 and AT06 unit tests each emitter-receiver pair in these non-ideal conditions.

2.4.4 Traceability Analysis 4

R04 concerns the integration between the sensor and power system. SP07 and SP05 outline this in terms of measurable quantities that AT03 verifies are correct.

2.4.5 Traceability Analysis 5

R05 concerns the budget of the final PCB, which is strictly defined by SP06. AT08 is to ensure that the total cost did not exceed the budget.

2.4.6 Traceability Analysis 6

R06 exists to ensure that the PCB has an appropriate size, which is more extensively explained by SP01, SP02, SP03 and SP04. AT01 and AT02 are an integration test for the sensing subsystem PCB and the rest of the hardware of the micro-mouse.

Chapter 3

Subsystem Design

3.1 Design Decisions

3.1.1 Design Decision Process

The flow chart in Figure 3.1 outlines the process taken to get to a final design in this instance.

The following sections outline each of the stages in Figure 3.1

3.1.2 Decide on general Transducer Circuit

Image Figure 3.2 shows a general circuit schematic was inspired by a lecture by UCLA on micro-mouse sensing [1]. This circuit is used throughout the design because it is simple and proven to work by the precedence of other engineers using it.

3.1.3 Build Breadboard Prototype Using On Hand Components to Decide on Appropriate Radiant Intensity and Reverse Light Current vs. Irradiance Curve for Photodiode

Due to the electromagnetic component of sensing, trying to use mathematics to deduce component values is hard. For this reason, a breadboard prototype was built to deduce ball-park parameters of the circuit.

At this stage, there were two options for how to realise the circuit with components on hand. It could be done with a single package infrared transducer (QRD1114-D), or a photodiode (SFH 205) and infrared LED (TSAL6100). It was decided to use the two discrete components because the distance between them could be changed, which may have been an important parameter to alter. It turned out that the most important component value in the circuit was R2 from Figure 3.2, and the distance between the components did not meaningfully change the circuit behaviour. R2 was chosen using trial an error from Table 3.1, and D1 from Figure 3.2 was driven at an arbitrary 10mA. This resulted in the circuit showed in Figure 3.5 having a voltage range of 700mA when moved from 60mm to 180mm

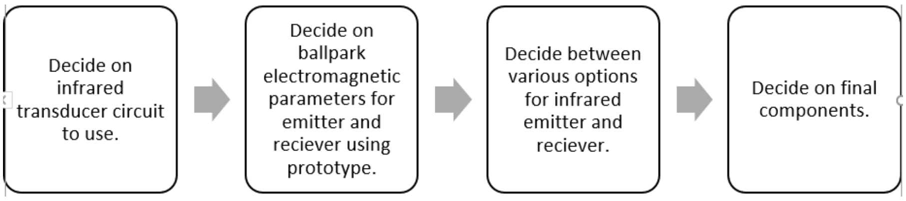


Figure 3.1: Flow Chart for Design Decision Process

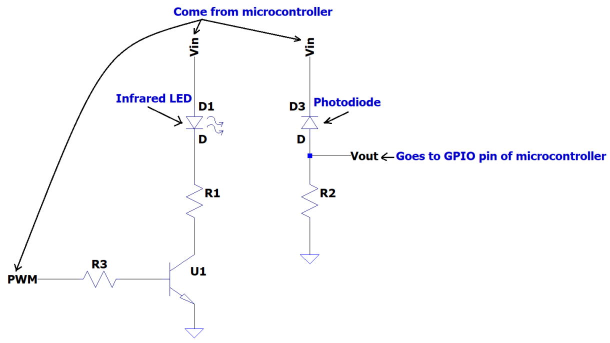


Figure 3.2: Simple Infrared Transducer Circuit

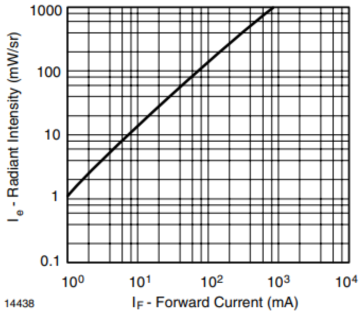


Figure 3.3: Radiant Intensity vs. Forward Current

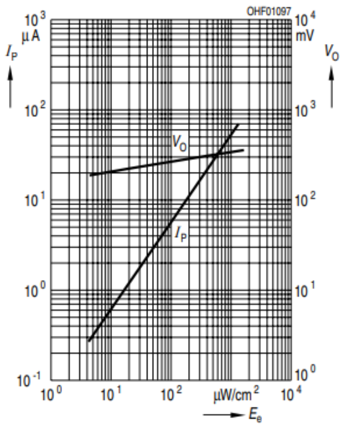


Figure 3.4: Reverse Light Current vs. Irradiance

from a wooden wall. These values satisfy SP05, SP07 and SP08. The circuit also satisfied SP09 when rotated through small angles and SP10 when slightly jiggled.

This prototype elucidated two characteristics to look for in components for the final circuit, which will give predictable results:

1. The TSLA6100 LED radiates 10mW/sr at 10mA as can be seen by Figure 3.3 (the 10mW/sr radiant intensity is the important characteristic).
2. The SFH-205-F photodiode has a reverse light current versus Irrandiance plot as shown in Figure 3.4.

Resistor (k\Omega)	Output at 60mm (V)	Output at 180mm (V)	Output at 250mm (V)
50	0.23	0.23	0.23
180	0.39	0.3	0.3
280	0.46	0.42	0.42
390	3.6	3.4	3.4
560	3.9	3.8	3.9
690	3.9	3.5	3.5
820	3.9	3.2	3.2

Table 3.1: Choosing R2 Using Trial and Error

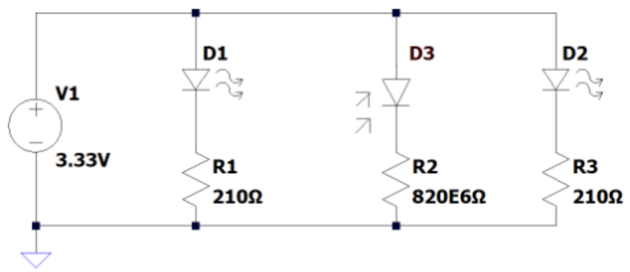


Figure 3.5: Prototype Circuit

Option	Infrared Emitter and Receiver	Response Time of Receiver	Extended Part Cost	Predictability
1	TEFD4300F and TSAL6200 (Infrared Diode and Photo-diode)	Very fast compared to the phototransistor found in the other two options.	Both components are only available as extended parts, and hence would cost $6.	TSAL6200 can radiate 10mW/sr at 3.3V and 22mA. TEFD4300F has a similar reverse light current vs. irradiance curve for photodiode used in prototype. Thus, this combination is very predictable.
2	QRD1113 (Reflective Object Sensor)	Slow compared to first option because it uses a phototransistor.	Only available as an extended part, but because it is a single part will cost $3.	Datasheets for these types of devices do not provide data that is easily comparable to the components of option 1, hence this device is unpredictable.
3	MHT153PTBT and TSAL6200 (Photodiode and Infrared LED)	Slow compared to first option because it uses a phototransistor.	Phototransistors come in basic varieties, hence only charged an extended fee for LED , amounting to $3	MHT153PTBT has a similar light current vs. irradiance curve for photodiode used in prototype, and TSAL6200 is the same as the LED used for option 1 - hence this combination is predictable.

Table 3.2

3.1.4 Decide Between Various Options for Infrared Emitter and Receiver

Table 3.2 below summarises reasons to either choose or reject three potential solutions for the emitter component and receiver component for the sensor. Only the extended part cost is included as it is typically an order of magnitude higher than the actual cost. Fast response times for the receiver will make it easier to read the output voltage into the microprocessor. Based on the table, option 1 was chosen because, although it is the most expensive, is the only one to have both a fast receiver response and predictability.

3.1.5 Deciding on How Many Emitter-Transmitter Pairs to use and in What Layout

After trying to fit only three emitter-transistor pairs onto a PCB in Kicad, it was found any more components would make it challenging to make a PCB that was small enough to meet the spacial specifications of the sensor. Hence, only three pairs was decided upon - two on the sides and one in front so that the mouse could use those three readings to identify where it can go.

3.1.6 Deciding on Final Components

The SS8050 BJT transistor was chosen for this circuit, as it can be driven to saturation whilst providing a 22mA current for the TSAL6200 LED. The following calculations show were done using the data sheets of the SS8050 and TSAL6200 to determine the base and collector resistor from Figure 3.2:

$V_{CE} = 0.25V$, $I_C = 22mA$, $I_B = 100\mu$A
for transistor to be in saturation and for LED to emit 10mW/sr at V_{CC} =3.3V. LED voltage drop will be 1.2V at this current.

V_{CC} - $R_B I_B$ - $V_{BE} = 0$
$3.3V$ - $R_B \times 100\mu A$ - $0.7 = 0$
$\therefore \quad R_B = 26000\Omega$

$V_{CC} \quad V_D \quad R_C I_C - V_{CE} = 0$
$3.3V \quad - \quad 1.2V \quad - \quad R_C(800\mu A) \quad - \quad 0.25 \quad = \quad 0$
$\therefore \quad R_C = 2.3125\Omega$

For these, the standard E24 values 27kΩ and 2.2Ω. The slightly higher value for R_B will increase the magnitude of the radiation emitted by the infrared LED and hence slightly increase the measured output voltage, however the slightly lower value chosen for R_C will decrease the measured output voltage. Consistent with the 820Ω resistor that was used for current limiting the photodiode in the prototype, an 800Ω was used.

3.1.7 Final Design

Figure 3.6, Figure 3.7a, Figure 3.7b and Figure 3.7c display the final PCB design. The final PCB is 111mm by 45mm which obeys SP02 and SP04.

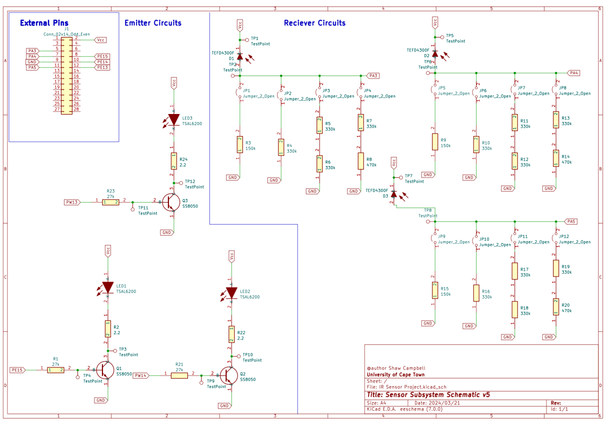
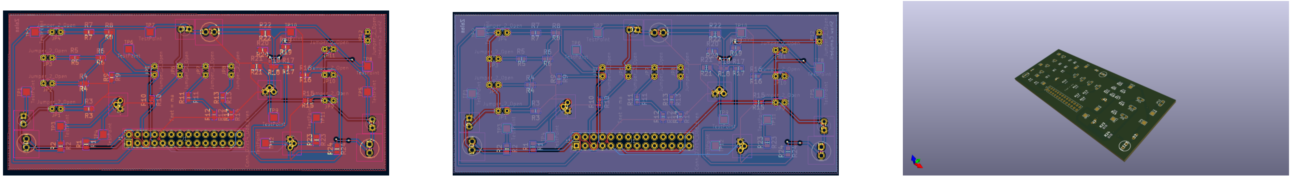


Figure 3.6: Schematic

3.2 Failure Management

Table 3.3 details the failure management processes implemented for the sensor design.



(a) Front PCB (b) Back PCB (c) 3D PCB

Figure 3.7: PCB

Table 3.3: Failure Management Processes

Name	Description
Multiple resistor values can limit photodiode	Four resistances can be connected to the photodiode using jumpers incase this resistance needs to be varied due to this resistance being so important in the prototype.
Test points added to important points	Test points added to base and collector of transistor to trace its operating point. Test points are also added across the photodiode to trace the output voltage.

3.3 System Integration and Interfacing

To integrate the subsystem with the rest of the system is shown is Table 3.4

Table 3.4: Interfacing specifications

Interface	Description	Pins/Output
I001	Sensor and microcontroller	• Base of Q3 to PWM13 • Base of Q1 to PE15 • Base of Q2 to PW14 • Anode of D1 to PA3 • Anode D2 to PA4 • Anode D3 to PA5
I002	Sensor to power subsystem	• V_{CC} to 3V3 (microcontroller) • GND to GND (microcontroller)

Figure 3.8 is an interfacing diagram showing how the sensing subsystem fits into the larger system.

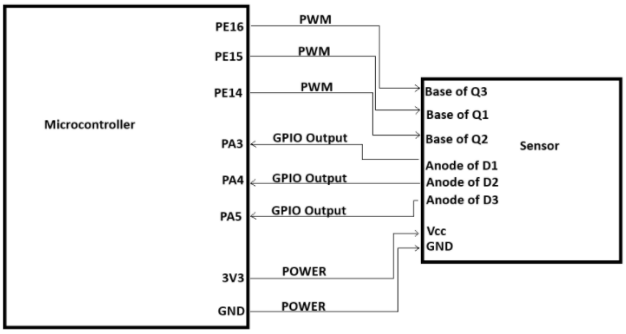


Figure 3.8: Interfacing Diagram

Chapter 4

Acceptance Testing

Table 4.1 shows the subsystem acceptance tests for the subsystem, how to carry them out and what constitutes a pass or fail.

4.1 Critical Analysis of Testing

Table 4.2 shows the result of each acceptance test.

4.1.1 AT01

The PCB male pins did fit into the female pins of the micro-mouse, however the physical size of the board was too large to not interfere with the wheels of the micro-mouse. This occurred due to an incomplete prior acknowledgement of the context of the sensor - specifically the relative position of the wheels to the sensor.

4.1.2 AT09

After continuity testing the LEDs and photodiodes, it became evident that the LEDs were biased in the correct direction, but the photodioes were not. Furthermore, the LEDs and photodiodes were not placed correctly, as shown Figure 4.1. These problems occured because of mistakes made in creating a KiCad model of the PCB. The LEDs and photodiodes were removed from the PCB and soldered back on to correct these problems.

The PCB was not populated with the transistors Q1, Q2 and Q3 which were meant to modulate the infrared LEDs, and resistors R2, R22 and R24 that were meant to limit the current flow into the LEDs and act as the collector resistances for Q1, Q2 and Q3.

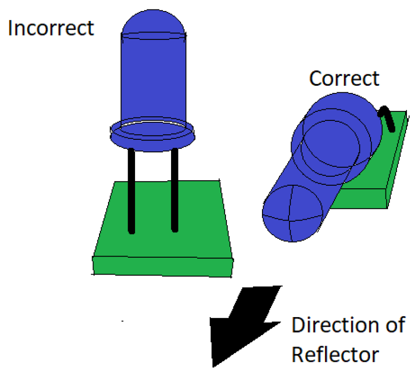


Figure 4.1: Illustration of Correct Position of LEDs and Photodiodes

Test ID and Description	Testing Procedure	Pass/Fail Criteria
AT01: Verify that PCB properly connects to motherboard pins and fits onto motherboard without mechanically interfering with other systems.	- Try to fit the male pins of the sensor into the female pins of the motherboard.	Pass if sensor male pins fit into micro-mouse female pins without occupying the space taken by other components.
AT02: Verify that PCB size does not dramatically reduce turning radius of micro-mouse.	- Measure the length and breadth of the sensor PCB.	Pass if measurements agree with SP02 and SP04.
AT03: Verify that the LED current is not too great.	- Measure the current flowing into the LED.	Pass if measurements agree with SP05 and SP07.
AT04: Verify that output voltage is appropriate at given distances.	- Measure the output voltage of the sensor circuit at 60mm, 180mm and 250mm away from a wooden surface.	Pass if voltage ranges by at least 0.5V between 60mm and 180mm, and if voltage has an ambient reading at 250mm.
AT05: Verify that output voltage does not vary drastically when rotated through small angles	- Measure the output voltage of the sensor circuit from 60mm from the wooden wall normal to the wall, and rotated 15 and -15 degrees.	Pass if voltage changes negligibly when rotated through 15 and -15 degrees.
AT06: Verify that output voltage does not vary drastically when slightly jiggled.	- Measure the output voltage of the sensor circuit from 60mm from the wooden wall when slightly	Pass if output voltage changes negligibly when sensor is slightly jiggled.
AT07: Verify that sensor turns on and off based on microcontroller PWM pin.	- Program microcontroller to toggle the infrared LEDs from 0V to 3.3V at a slow rate and view them through a camera to ensure that it is working.	Pass if the toggling of the infrared LED can be seen on the camera.
AT08: Verify that cost of PCB manufacture is below $30.	- Calculate the total cost of the PCB.	Pass if below $30.
AT09: Verify that PCB components are all present and placed correctly	- Compare PCB to schematic to ensure that all components are present. Ensure that LEDs and photodiodes are placed in correct direction using continuity tests.	Pass all components present and, LEDs and photodiodes are in correct direction.
AT010: Verify that all PCB traces are present and conducting	- Compare PCB to schematic to ensure that all traces are present, and use continuity tests to ensure that traces are conducting	Pass if all traces are present and conduct when continuity tested.

Table 4.1: Subsystem Acceptance Tests

Test ID	**Result**
AT01	Failed, but can be fixed by attaching a piece of PCB to extend the board.
AT02	Passed. The board matched the theoretical measurements.
AT03	Passed. The final current draw by the LED was 398.65A.
AT04	Passed. The final voltages were: 2.35V at 60mm, 2.34V at 180mm and 91.18mV at 250mm.
AT05	Passed. The output voltage varied by less than 10mV.
AT06	Passed. The change in voltage was negligible.
AT07	Passed.
AT08	Passed. The PCB came to a cost of $28.
AT09	Failed, but was fixed by soldering locally sourced components to PCB.
AT10	Failed, but was fixed by soldering wires onto board to short open connections.

Table 4.2

The reason for the resistors and transistors not being populated is unknown, but is likely because they were not in stock during the manufacture of the sensor. This was despite the fact that all chosen components were in stock (thousands of available items) when the PCB was ordered.

Since the ordered transistors are not locally available, another locally available model had to be chosen and soldered onto the PCB, along with a collector resistor such that the LEDs could be modulated at the correct intensity.

Since the base resistor is 27kΩ (which was chosen to save power, and theoretically would have driven the initial transistor into saturation), it would be difficult to drive the new transistor into saturation, sicne the resistance is so large - but it being in the linear region would work (while not being ideal in terms of switching speed and efficiency). For this reason, it was decided to use a 2N2222A NPN transistor without trying to find a transistor that would be driven into saturation, and to select the collector resistance based off of trial error, and based on whether the LED could be modulated (satisfying AT07), whether the current drawn by the LED was below 400mA (satisfying AT03).

Although testing of the output voltage is dealt with later in the report, it made sense to add it to the data used to select the collector resistance. later in the report, the photodiode current-limiting resistance is fine-tuned to achieve a desirable voltage range, but for this test it was set to 800kΩ. The output voltage was then measured at 60mm and 180mm from a wooden surface to observe whether or not the LED intensity (directly caused by the collector resistance) was over saturating the photodiode, or resulting in no sensing range at all. Figure 4.2 shows the data collected to choose the collector resistance for the transistors.

From Figure 4.2, it can be seen that all tested collector resistances resulted in AT07 being satisfied. The 39 resistance resulted in the greatest output voltage range, and resulted in a current draw within 400mA. The voltage ranges were lower than theoretically anticipated, hence the the largest one was chosen, for a current within 400mA - implying that the 39Ω resistor was chosen.

Figure 4.2 shows the data collected when using trial and error to choose the collector resistance.

Collector Resistance(Ω)	LED Current (mA)	LED Modulation	Vout Range from 60mm to 180mm (mV)
1000	73.9	AT07 passed	3.67
500	123.67	AT07 passed	3.56
200	261.33	AT07 passed	11.12
100	331.7	AT07 passed	27.67
50	395.34	AT07 passed	35.46
39	398.65	AT07 passed	38.34
10	405.78	AT07 passed	53.65

Figure 4.2: Trial and Error Data for Selecting Collector Resistance

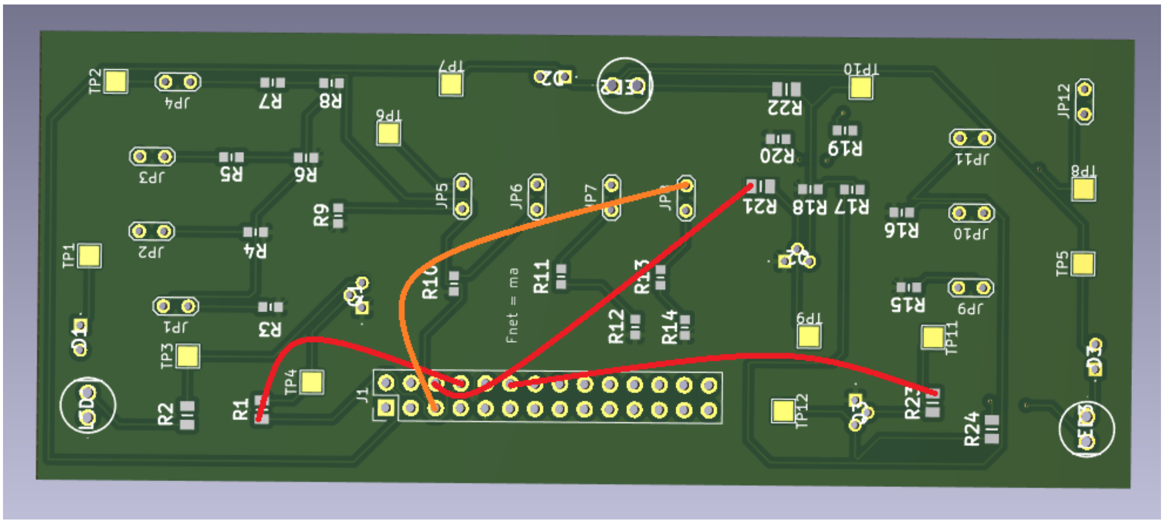


Figure 4.3: Wires Soldered onto PCB Board Represented by Solid Red and Orange Lines

4.1.3 AT10

After reviewing and continuity testing each trace on the PCB, it was determined that three connections were erroneously not added during the creating the KiCad model. These connections had to be soldered on using wire as illustrated in Figure 4.3 below.

4.1.4 AT104

There are four jumpers following each photodiode that can be shorted to limit the photodiodes by either 150kΩ, 330kΩ, 660kΩ and 800kΩ. From the critical analysis of AT09, it is clear that shorting the photodiodes to the 800kΩ resistor is optimal, to at least get a 38.34mV output voltage range. This voltage range however does not meet the pass criteria for AT104. This resulted in another resistor needing to be placed across the jumper. To decide on the value of this resistor, another trial and error test was run as shown by Figure 4.4

As can be seen in Figure 4.4, using a 580kΩ results in a far better output voltage that theoretically was predicted, using the entire voltage range of the GPIO ports of the microcontroller - hence this resistor was used.

Resistance(kΩ)	Voltage at 60mm (V)	Voltage at 180mm (V)	Voltage at 250mm (V)	Ambient Voltage(mV)
100	0.524	0.521	17.34	14.56
200	0.934	0.923	24.55	26.34
300	1.72	1.67	67.34	57.34
500	2.35	2.34	91.18	94.76
580	2.93	2.86	112.76	105.23

Figure 4.4: Data for Choosing Photodiode Resistance

```
while (1)
{
    HAL_GPIO_WritePin(IRLED1_GPIO_Port, IRLED1_Pin,SET);
    HAL_Delay(1000);
    HAL_GPIO_WritePin(IRLED1_GPIO_Port, IRLED1_Pin,RESET);
}
```

Figure 4.5: C Code that toggles D3 every second

4.1.5 AT107

Following from the discussion about AT09, toggling the base voltage from 0V to 3.3V of the transistors successfully toggled the infrared LEDs, as viewed from a phone camera that make the LED's appear pink when they emit light.

The following C code in toggles D3, which successfully toggled D3 every 1s:

Chapter 5

Conclusion

The sensor has a good output voltage range that utilises its entire power supply to range distances accurately. Its output voltage exceeded the theoretical expectations, and specifications. This sensor could also successfully interface with the micro-controller to toggle the infrared LEDs. This culminates in a working sensor that would be able to provide sensing functions to a micro-mouse.

The excellent voltage range comes with the fact that the transistors and LED limiting resistors were locally sourced due to KiCad errors - displaying modelling errors, along with having to solder extra wires to the PCB. The limiting resistors for the photodiode also needed an additional 580kΩ resistance to work well - indicating a failure in design. However, the photodiode was mentioned to be difficult to work with analytically, and since it was designed to be limited by a massive 800kΩ, the extra 580kΩ is not as much as a failure as it may seem as 580 is only 72.5 percent of 800. The PCB board being incident with the wheels of the micro-mouse was arguably the biggest mistake - a clear failure to consider the context of the sensor.

5.1 Recommendations

Apart from the trivial KiCad and context errors displayed, this report displayed clearly the non-trivial nature of predicting how photodiodes work in circuits - due to their interaction with electromagnetic waves. When working with these devices, one should try to prototype with the one they are planning to use, or at least plan in advance to use a variety of different resistor values to current limit it.

The technique of choosing the resistor used to current limit the photodiode in this report may be acceptable if an error of 72.5 percent can be compensated for. It seems that the technique used in this report at least predicted an appropriate photodiode resistance within an order of magnitude. Given the fact that resistors are cheap, this may be a valid technique to replicate, to get an idea of what resistance one might use for their photodiode.

Bibliography

[1] U. IEEE, “Micromouse 2021 lecture 4: Ir sensors,” 2021. [Online]. Available: https://www.youtube.com/watch?v=fwOo8e-dVag&t=1419s

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