Final Design Report

Micromouse X Subsystem

Prepared by:
Justin Cross (CRSKAT005)

Prepared for:
EEE3088F
Department of Electrical Engineering
University of Cape Town

May 17, 2024

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Chapter 1

Introduction

1.1 Problem Description

The aim of the project is to design the hardware for a maze-solving robot known as a micro-mouse. Within designing the hardware, there are four modules that are involved, namely the motherboard, the processor, the power and the sensor. By being the supplied an STM32F051 processor board, the greater project requires the designing and construction of the power and sensor modules for the micro-mouse. The specific problem discussed in this report is the design of the sensor module required for the detection of any obstructions in the vicinity of the micro-mouse's path. The sensor will serve as the 'eyes' of the robot.

1.2 Scope and Limitations

The project discussed in this report focuses solely on the task of creating the sensing/detection characteristics of the micro-mouse. It does not elaborate on the design characteristics of the power module of the greater project, but merely describes it's relationship and integration with the power specifications in that module.
The project is limited by the need to meet specified budget requirements, as well as component availability from the JLCPCB parts website. The small size of the sensing PCB itself, along with the use of only one side of the board, provides limitations to components sizes, testing areas and the overall development of the sensing module.

1.3 GitHub Link

https://github.com/justincross10/sense-our-power/tree/main

Chapter 2

Requirements Analysis

2.1 Requirements

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

Table 2.1: Table showing the requirements of the sensing subsystem.

Requirement ID	Description
UR01	The system must be able to detect whether there is an object in front or on the sides of the micro-mouse.
UR02	The design should be reliable with repeatable outputs to prove the system works over an extended period of time.
UR03	The design must meet the strict budget requirements for manufacturing of the boards.
UR04	It must have a switching behaviour to save power when not in operation.
UR05	It must utilise a code to interface the sensor with the processor to prove it senses an obstacle.
UR06	A suitable amount of current and power must be utilised by the system to ensure the battery does not drain during the maize solving process.

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	The sensor module will have a detection range from 0 - 180mm away from any sensed obstruction.
SP02	The LEDs from the processor should repeatably light up in the presence of obstacles, over an extended period of time to ensure reliability.
SP03	The cost of ordering two assembled boards should be under 30 USD.

SP04	Using the GPIO pins of the STM32F051, the sensor will be able to have switching means for its emitters. If the sensor voltage does not reach a logic high level after 120 seconds of operation, the emitters will turn off.
SP05	According to the written program uploaded to the STM32F051, the 3 LEDs found on the processor board will indicate whether an obstacle is sensed. (LED 1 = left wall, LED2 = front wall, LED 3 = right wall). No additional LEDs will be used.
SP06	The sensor circuitry will not exceed a current value of 150mA to allow for the battery life to be sustainable for the maize solving process.

2.3 Testing Procedures

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

Table 2.3: Table showing acceptance tests

Acceptance Test ID	**Description**
AT01	Obstruction detection test: The sensor module will be tested in an applicable facility to determine it's range detection accuracy in relation with SP01.
AT02	Sensor reliability test: The sensor will undergo the obstruction detection test for a prolonged period of time to esnure the modules reliability.
AT03	BOM test: The Bill of Materials for components and PCB design is submitted to JLCPCB's website to determine the manufacturing cost.
AT04	Power reduction test: The voltage drop across the emitters will be tested after the emitter branches have been switched off to determine power saving functionality.
AT05	Processor LED test: The behaviour of the processor LEDs will be examined during the obstruction detection test, to test that the LEDs are functioning in accordance to the written program.
AT06	Power efficiency test: The amount of current drawn from the battery will be measured to ensure it is below the specified amount from SP06.

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	UR01	SP01	AT01
2	UR02	SP02	AT02, AT01
3	UR03	SP03	AT03
4	UR04	SP04	AT04
5	UR05	SP05	AT05
6	UR06	SP06	AT06

2.4.1 Traceability Analysis 1

From UR01, detection of obstacles in front or on the sides of the micro-mouse, SP01 can be derived - which is important for the navigation of the micro-mouse through the maize. This relationship is verified through AT01, the obstruction detection test. If the test proves detection of obstacles within the specified range, the specification SP01 is met.

2.4.2 Traceability Analysis 2

From UR02, reliability through repeatable outputs over an extended period of time, SP02 can be derived. This is proven through AT01 and AT02 - by performing the AT01 over a prolonged period of time (AT02), we can certify SP02. This is required to prove consistent navigation performance within the maize.

2.4.3 Traceability Analysis 3

From UR03, adherence to strict budget requirements, SP03 is derived. A budget of 30 USD for two assembled PCBs needs to be met in order for the boards to be ordered. This is verified through AT03, where the bill of materials is submitted to the manufacturers website (JLCPCB) to determine the cost of manufacturing.

2.4.4 Traceability Analysis 4

From UR04, creating switching behaviour to save power when not in operation, SP04 is derived. By running acceptance test AT04, the consumption of power by the emitters of the sensor can be measured to determine if battery power is being saved when the emitters are on versus when they are off.

2.4.5 Traceability Analysis 5

From UR05, utilising a code to interface the sensor with the processor board, SP05 can be derived. This program is vital in creating the correct LED behaviour for sensing obstacles. Using AT05, we can examine the behaviour of the LEDs to ensure the program is running correctly.

2.4.6 Traceability Analysis 6

From UR06, utilizing a suitable amount of current and power to ensure the battery doesn't drain during the maize solving process, SP06 is derived. By conducting AT06, the power efficiency test, we can determine and verify that the current drawn from the battery is below 150mA.

Chapter 3

Subsystem Design

3.1 Design Decisions

The following design decisions are categorized into different component focuses listed below:

Sensor circuitry decisions:
Infrared sensors were required in order to represent a detection of obstacles by the micro-mouse. A table showing the decisions taken for the sensor circuitry is found below.

Sensoring Component	Part ID	Decision	Reason
Phototransistor	PT204-6B	Yes	Peak wavelength sensitivity of 940nm, which is ideal for emitter-sensor relationship. The maximum rated collector current is low (20mA). It is also an inexpensive component, costing only 0.04USD. The half angle is 30 degrees. (improvement from SFH203 PFA)
Photodiode	SFH203 PFA	No	The half angle of 75 degrees was too wide for the sensing requirements, which would result in an overlap of detection between the left, front and right detection sides of the MM.

Table 3.1: Table comparing the design decisions for the sensor circuitry.

Emitter circuitry decisions:

All the emission components were Infrared LEDs as the sensor detects objects using only IR light, and a table comparing the design decisions for the desired emitter is given below.

IR LED	Decision	Reason
VSLB3940	Yes	The wavlength of peak sensitivity is 940nm, which matches the chosen sensor. The radiant intensity is satifcactory being 65mW/sr @100mA typically. Although this is lower than the HIR333C-A, one could just use two emitters for each sensing side of the MM. The forward voltage of the component is also suffice, being only 1.35V typically.
HIR333C-A	No	The wavelength of peak sensitivity is 850nm, which is too low for the decided sensing component. The radiant intensity was satisfactory, being 140mW/sr @100mA.
TSAL6100	No	Ideal component with matching peak wavelength of 940nm, and radiant intensity of 170mW/sr @100mA. No stock for this component.

Table 3.2: Table comparing the design decisions for the emission component circuitry.

In order to create switching mechanisms to save power when the subsystem is not in operation, a transistor configuration was created in series to act as a switch, controlled by the GPIO pins of the microcontroller.

A table showing the characteristics of the transistors considered and chosen is shown below.

Type	NPN/PNP	Part ID	Decision	Reason
BJT	NPN	SS8050-C2150	Yes	Cost effective basic part(0.01 USD). Gain value of 250 for desired collector current which resulted in low base current to drive it into saturation.
BJT	NPN	MMDT2222A	No	It is an extended part, which would result in extra labour costs to mount it. It has two built-in BJTs into the component which would make it suitable for board size compatibility and spacial effectiveness.

Table 3.3: Table comparing the different switching components considered

Specified resistor values were required for the base branch of the transistor as well as the collector branch. The target collector current was 85mA. Using the graphical relationships from the BJT datasheet as well as calculations, the required resistor values are shown below:

For 85mA:
$R_c = \frac{V_{\text{in}} - V_{\text{LED max}}}{I_c}$
$= \frac{3.5-1.6}{0.085} = 22ohms$
Therefore according to the SS8050-C2150 data sheet,
Using a gain of 250 @ 85mA in order to turn BJT on:
$I_b = \frac{I_c}{250} = 0.34uA$
Therefore, base resistance $R_b = \frac{V_{\text{microcontroller}} - V_{\text{BE}}}{I_b} = \frac{3.3-0.7}{0.00034} = 7647ohms$
Therefore, two E12 resistors in series being, 2.7k ohms and 4.7k ohms, were used in the base branch.

Voltage regulation decisions:

Due to the battery behaviour charging and discharging between a voltage range of 3.0V - 4.2V, but largely maintaining a voltage range between 3.5V - 4.2V it was decided that a linear voltage regulator would be used to regulate the voltage input into the sensor subsystem.
A table comparing the different voltage regulator decisions is shown below:

Part ID	Decision	Reason
AMS1117-3.3	Yes	Basic part, preventing extra labour costs. It has an adjustable voltage range of 3.3V to 5V which is ideal for this subsystem.
LM317	No	Component characteristics had ideal behaviour for this design, with an output voltage adjustable over a 1.2V to 37V range. The component is an extended part and the extra labour cost also made it unaffordable.

Table 3.4: Table comparing different voltage regulators considered

A constant input voltage of 3.5V was desired for the sensing subsystem from the battery input. This required calculations for a resistor branch for the voltage regulator to produce such a voltage. These calculations are found below:

$V_{\text{out}} = V_{\text{ref}}(1 + \frac{R_2}{R_1}) + I_{\text{adj}}(R_2)$
Where:
$V_{\text{out}} = 3.5V$
$V_{\text{ref}} = 1.25V$

$I_{\text{adj}} = 55uA$

By substituting the above information, and using E12 series resistors in relationship to one another, R1 = 220 ohms and R2 = 390 ohms. To achieve an output voltage of 3.5V.

3.1.1 Final design

The final design depicted below was based off the design decisions made in the above subsection. The design uses 6 emitter branches in total, 2 for the left side, 2 for the front, and 2 for the right side. This was done to enhance the IR radiation from the emitters to detect object.

Each emitter pair is accompanied with one sensing circuitry system.

The voltage regulator is connected to the battery pin of the pin header to maintain a constant voltage input into the subsystem.

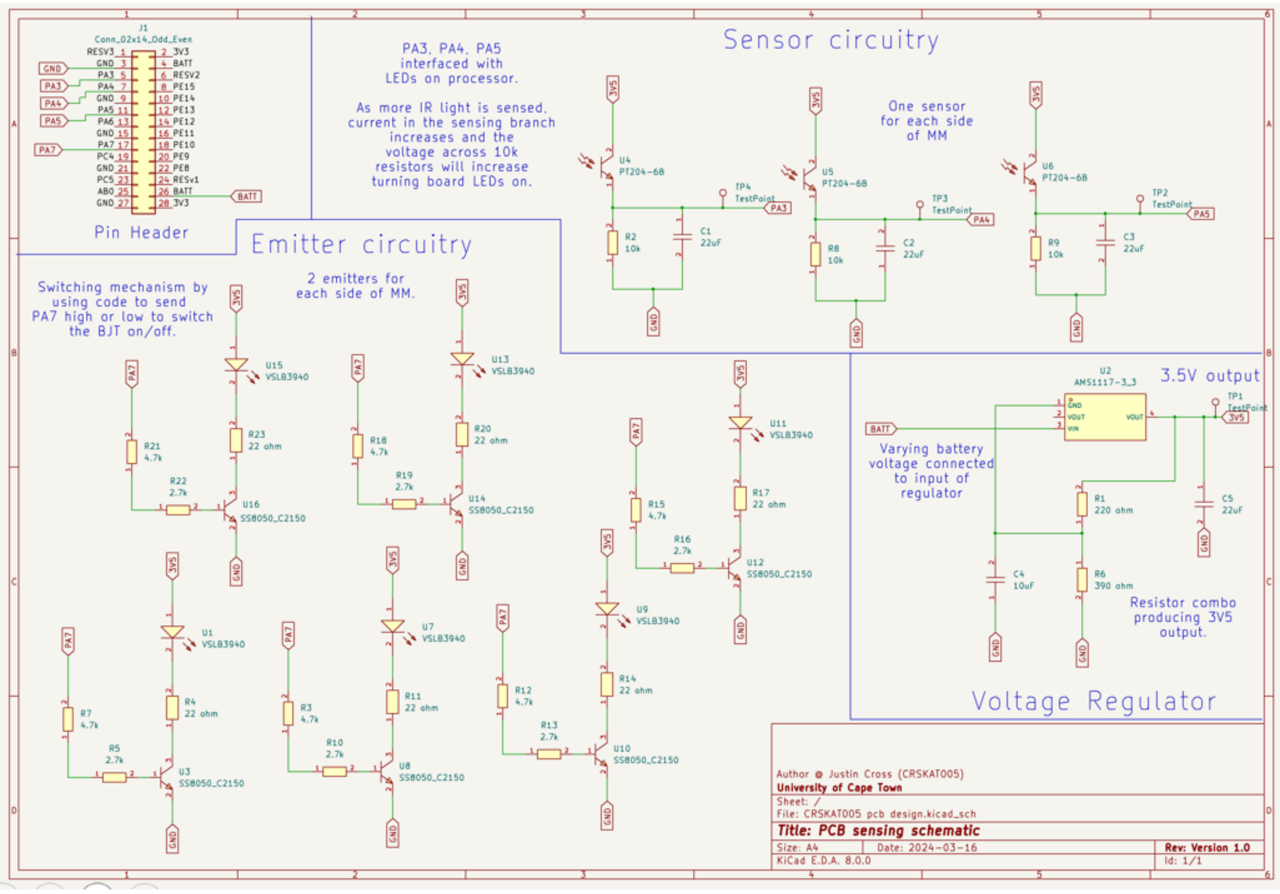
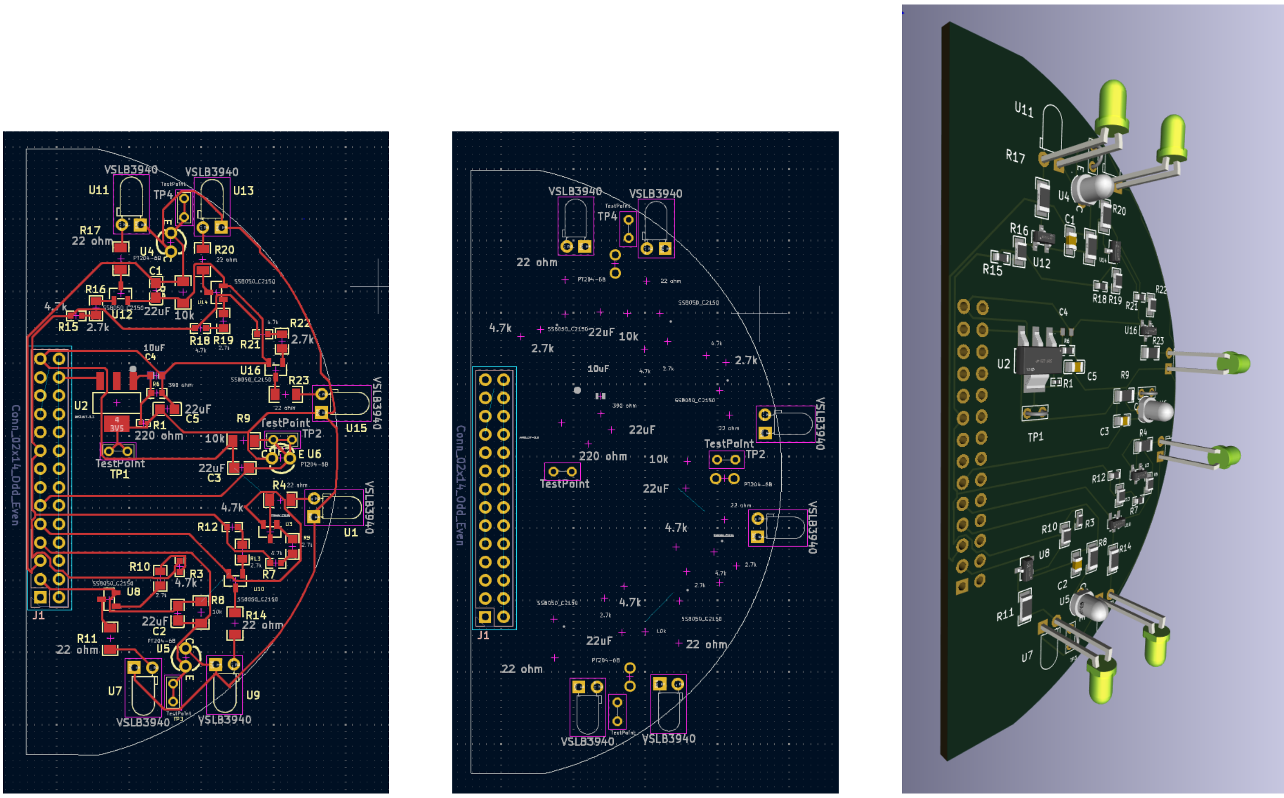


Figure 3.1: Schematic



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

Figure 3.2: PCB

3.2 Failure Management

Below is a table indicating the different steps taken for failure management in the sensor subsystem.

Table 3.5: Table showing the different failure management procedures

Name	Description
Test point TP1	This test point serves to determine the correct functionality and voltage requirement of 3,5V at the output of the voltage regulator.
Test points TP2, TP3, TP4	These test points are used to test and determine if the written program to interface the LEDs on the processor board correctly match the behaviour at the outputs of the sensor circuitry.
Sensor-Emitter relative positioning	Each sensor is placed below and behind the two emitters coupled in the relationship to prevent immediate sensing of IR light by the sensor before it has been reflected off a detected object.
Noise filtering capacitors	Capacitors are connected in parallel with voltage dividing resistors in the sensor circuitry to reduce the effect of noisy signals at the output.

Stability capacitors	Capacitors in the voltage regulation circuitry provide stability from input ripple voltages and high frequency noise.

3.3 System Integration and Interfacing

To integrate the subsystem with the rest of the system, the sensor system uses pin headers that will be connected to the pin headers of the processor board. A table showing the integrated relationships is shown below.

Table 3.6: Interfacing specifications

Interface	Description	Pins/Output
I001	Sensor subsystem to STM32F051 processor board	• MISO: Sensor Output to STM PA3, PA4, PA5 (Analog output) • MOSI: STM PA7 (3V3 input) to Sensor Input • SCLK: STM SCLK to Sensor SCLK • CS: Sensor CS to STM GPIO • GND: Sensor GND to STM GND
I002	Sensor subsystem to Power (Independent battery system)	• VCC: Battery VCC (BATT) to Sensor VCC
I003	PC Interface to Processor Module	• USB: PC USB to Processor Serial port

To visualize the interfacing of the sensor module with the rest of the micro-mouse system, a system interfacing diagram is shown below.

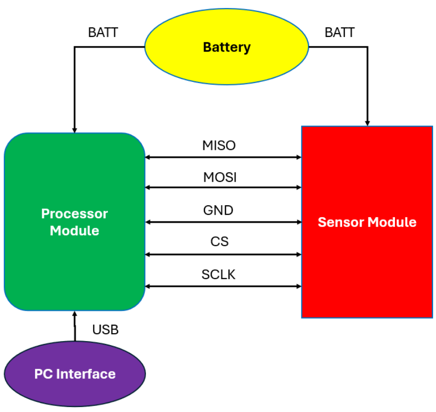


Figure 3.3: System Interfacing Diagram

Chapter 4

Acceptance Testing

4.1 Tests

Table 4.1: Subsystem acceptance tests

Test ID	Description	Testing Procedure	Pass/Fail Criteria
AT01	Sensor module is powered when connected to the battery terminal.	• Connect the sensor subsystem to battery. • Test the voltage drop across the battery input into the sensor subsystem and ground using oscilloscope probes to determine if power is entering the system. • Test the voltage drop across the positive and negative terminals of the battery only.	• Pass: The voltage drop across the sensor subsystem should match the voltage drop across the battery terminals. • Fail: No voltage reading across the sensor subsystem.
AT02	Existence of current in the emitter branches.	• Using a multimeter, measure the current flowing through each of the emitter branches (when BJTs are on) - by measuring the current flowing through each IR LED using the multimeter probes.	• Pass: Correct reading of 85mA< and <100mA measured flowing through emitters. • Fail: Current reading of 0mA.
AT03	Power saving by turning the emitter branches off using the transistor.	• PA7, connected to the base of the BJT in the emitter branches, is sent to a logic level low, after 120 seconds of no sensing, to turn the BJTs off and hence turn the emitter branches off. • The current through the IR LEDs is once again measured using a mulitmeter and its probes.	• Pass: There is a current reading of 0mA across the IR LEDs. • Fail: There is still a current reading of 85mA< and <100mA across the IR LEDs.

AT04	Determination of the performance of the voltage regulator and whether it suitably functions as desired in module.	• Using the test point (TP1) at the output of the voltage regulator (AMS1117), the voltage at the output will be tested using the oscilloscope and its probes.	• Pass: Voltage at the output of the regulator is measured to be +- 3.5V. • Fail: Voltage at the output of the regulator is less than 2V.
AT05	This test aims to determine the performance of the sensor at different distances from an obstacle.	• By moving the sensor subsystem closer and further to obstacles in the left, right and forward directions. • Measure the voltage reading across the test point (TP1,2,3) at the output of each sensor point using the oscilloscope and its probes.	• Pass: from 60-180mm there is a voltage change of at least 0.3V increase from the measured voltage at 180mm from the obstacle. • Fail: Zero fluctuation in voltage or no voltage reading at all at test point.
AT06	A test to determine the amount of current drawn by the sensor module from the battery.	• The current entering the subsystem at the output of the voltage regulator (TP1) will be measured using a multimeter and its probes to determine how much current the subsystem is using.	• Pass: The current input into the subsystem is below 150mA. • Fail: The current at the input exceeds 150mA.
AT07	Processor LED indication of obstacle detection for different directions.	• Moving the sensor subsystem closer and further to obstacles in the left, right and forward directions.	• Pass: At 60mm away from the obstacle, the specified LED for the direction the obstacle is in should turn on. • Fail: At 60mm, the LED for that specified direction does not turn on.
AT08	Budget test (This is a business acceptance test)	• Submission of the BOM and CPL files to JLCPCB manufacturing website.	• Pass: Cost of materials for production of two boards is under 30USD. • Fail: Cost of materials is over 30USD.
AT09	Repeatability test	• AT05 and AT07 are repeated to ensure reliability of the sensor modules behaviour.	• Pass: Pass criteria for AT05 and AT07 repeatably occurs. • Fail: No repeatability of the pass criteria for AT05 and AT07.

4.2 Critical Analysis of Testing

Table 4.2: Subsystem acceptance test results

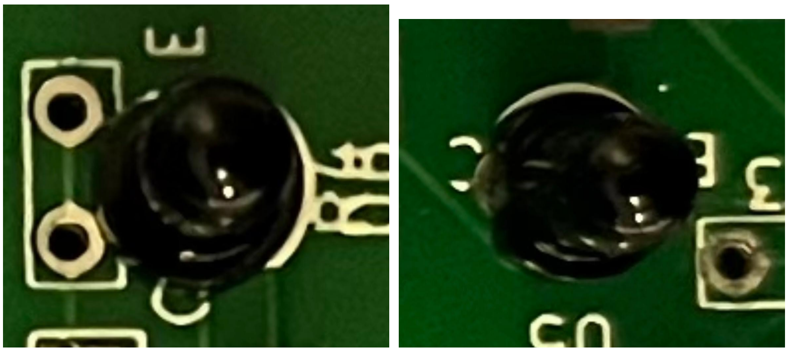
Test ID	Description	Result
AT01	Sensor module is powered when connected to the battery terminal.	Pass
AT02	Existence of current in the emitter branches.	Pass
AT03	Power saving by turning the emitter branches off using the transistor.	Pass
AT04	Determination of the performance of the voltage regulator and whether it suitably functions as desired in module.	Fail
AT05	This test aims to determine the performance of the sensor at different distances from an obstacle.	Pass
AT06	A test to determine the amount of current drawn by the sensor module from the battery.	Fail
AT07	Processor LED indication of obstacle detection for different directions.	Fail
AT08	Budget test (This is a business acceptance test)	Pass
AT09	Repeatability test	Fail

Below is a discussion and critical analysis of the 5 most important acceptance tests performed on the sensor PCB subsystem.

4.2.1 AT01

The first and most significant test was that of the ability of the sensor module to draw power from the battery in order for it to perform as expected within the other requirements of the subsystem.

Observations:
Upon arrival of the PCBs, the boards needed to be examined to ensure that the two populated PCBs that were ordered had all the required components mounted correctly on each board. This was done to ensure there were no unintended breaks or shorts in the flow of current through the subsystem.
It was observed that the front sensing phototransistor was placed in reverse with the collector and emitter legs inverted. (figure shown below)



(a) Incorrect placement of phototransistor

(b) Correct placement of phototransistor

No other components were placed incorrectly or missing.

Testing and Result:
Once the misplaced components were correctly re-placed, continuity tests were done on all components to ensure correct functionality, and finally 4.2V was supplied from a DC power supply to the BATT pin at the input to the subsystem. The voltage drop from the input of the subsystem to ground matched the voltage drop across the terminals of the power supply, which resembled a passed acceptance test.

4.2.2 AT04

The determination of the performance of the voltage regulator was vital with respect to the performance of the rest of the subsystem. If the voltage regulator did not perform as required, there would be insufficient power delivered to the rest of the module.

Testing and Result:
Using a DC power supply connected to the BATT pin, the voltage at TP1 was assessed as the input voltage into the regulator was increased, starting at 1V and finishing at 4.2V.
It was discovered that the voltage at the output of the regulator (TP1) never exceeded 1V. This resulted in a failed acceptance test.
Through analysis of datasheets once more, it became apparent that the AMS1117-3V3 has a dropout voltage of 1.5V. This characteristic was overlooked in the selection of the voltage regulator.

Solution:
To create functionality of the sensor module, it was decided that the voltage regulator would be removed from the PCB, in order to supply the necessary power to the rest of the board.
The design lacked the necessary jumper point in order to short the voltage regulator connection. Therefore, a 1.2 ohm resistor was soldered onto the board from the Vin pad of the regulator footprint to the Vout pad.
An image of the solution is given below:

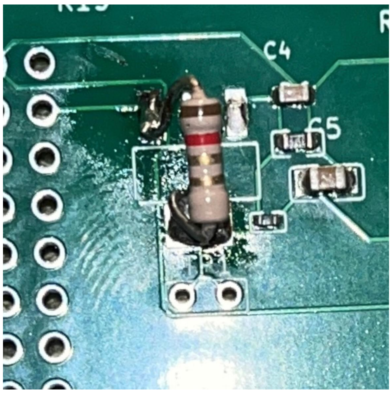


Figure 4.2: Figure showing the resistor replacement for the voltage regulator.

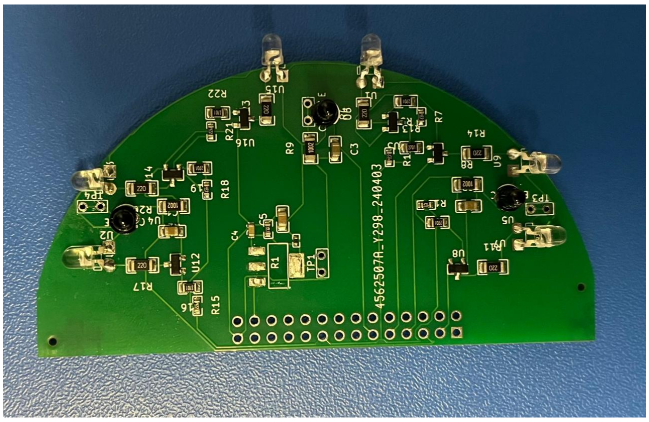
The following calculations were made to determine the resistance value that would be necessary to supply the required amount of power to the rest of the board and more specifically, to the emitter branches which needed larger current value to operate.
$R = \frac{V_{\text{drop across R}}}{I_{\text{in}}} = \frac{0.5}{0.4} = 1.25$ ohms.

4.2.3 AT05

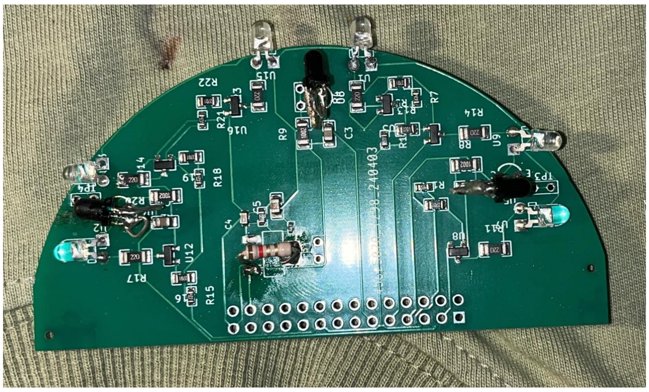
This test served to determine the performance of the sensors at different distances away from an obstacle in the left, right and forward directions.

Observations:
Upon arrival of the boards and after the reparation of the voltage regulator issue discussed in AT04, the PT2S04-6B's were tested against different obstacles in the left, right and forward directions.
It was discovered that the sensors were not placed in the correct directions in order to maximise sensing of reflected IR light.

Solution:
This required the phototransistors to be desoldered, and have extra conducting wire soldered onto the ends of the legs in order to be bent in the correct sensing direction.
The figure below indicate the changes made to the sensors:



(a) Sensor upon arrival



(b) Sensor after moderation

Due to the tedious processes involved with the soldering of the conducting wire onto the PT204-6B legs, the left and right phototransistors were subsequently damaged and had no voltage changes when moving toward and away from obstacles in their respective sensing directions.
The solution presented to this issue was to, once again, desolder the damaged sensors and replace them with new phototransistors. To avoid further damge to any more PT204-6B components between the two populated boards, it was decided that the phototransistors found within two QRD1114's would be mounted onto the sensing PCB in replacement. These served as a valid replacement as both the QRD1114 and the PT204-6B have the same wavelength of maximum sensitivity being 940nm.

Testing and Result: After finalising the sensors used on the board, the sensors were once again tested at 4.2V DC input and the results (from an oscilloscope) are listed in the table below.

Direction	60mm	180mm
Left	2.00V	1.60V
Right	1.00V	0.70V
Forward	1.45V	1.00V

Table 4.3: Test results from sensing obstacles in different directions at different distances.

With the voltage changes in each direction all being greater than or equal to 0.3V from 180mm - 60mm, the acceptance test was passed.

4.2.4 AT02

An essential part of the sensor module was ensuring that there were functional emitters receiving enough current to enhance the sensing distances of the phototransistors.

Testing and Result:
After the removal of the voltage regulator, the emitters were capable of receiving sufficient power to radiate intense amounts of IR light. The transistors (used as a power saving mechanism) were set to a logic level high in order to allow current to flow through the emitter branches and the test to be conducted. This was done temporarily by using a second channel from the DC power supply to send 3.3V input to PA7 (base of transistors) of the sensor module pin-out.
The allowable range of current readings were >85mA and <100mA. Current values greater than 100mA would exceed the maximum current rating from the data sheet for the VSLB3940 and would possibly cause damage to the emitters. The emitter current readings fluctuated between 95 - 100mA. This resulted in a passed acceptance test.

4.2.5 AT07

This test served as an indicator as to whether obstacles were being detected in the respective sensing directions by turning on three specified LEDs for different directions on the STM32F051 microcontroller.

Testing and Result:
In order to indicate which direction was being sensed by the sensing module - LED @ PB7 was assigned to the left sensor, LED @ PB6 was assigned to the front sensor, and LED @ PB5 was assigned to the right sensor.
A program was then written to interface the LEDs with their respective sensors. The sensors were set to an analog output and using the ADC functionality of the mircocontroller, these outputs were used to toggle the LEDs.
In order to switch the LEDs between logic level high and low at different voltage values, the following ADC conversions were calculated to implement into the program:

$ADCvalue = \frac{V_{\text{out}}}{3.3}(4096)$
According to AT05 this resulted in:
$V_{\text{out left}} = 2482@2V$
$V_{\text{out right}} = 1241@1V$
$V_{\text{out front}} = 1750@1.45V$

The above values were placed in the program, but the program did not run as expected and could only output all 3 lights at a logic level high when the code was flashed onto the microcontroller. This resulted in a failed acceptance test.

Chapter 5

Conclusion

In accordance to the problem description, the designed sensor subsystem was successful in creating the necessary hardware for the sensing module of a micro-mouse. Not only is the necessary hardware in place, but it also accurately senses objects in the left, right and forward directions as indicated in the above acceptance tests.

The subsystem did not deliver passing results to meet all the requirements set out at the beginning of the report.

Those that failed included the sensors ability to draw a sufficient amount of current in order for both the power and sensor modules to operate from the rated battery power. The system also could not be interfaced with a program that could deliver detection of obstacles through turning LEDs on and off on the microcontroller.

In conclusion, the main required outcome of this project was to create a subsystem that could repeatably detect obstructions. Along with this achievement, the module stayed true to the scope and limitations as demanded in the project description. The above sensor can be described as competent, yet there are improvements that could have been made to enhance the performance of this module.

5.1 Recommendations

By analysing what met expectations and requirements and what did not, multiple recommendations were learnt following the completion of the project.

The necessity for jumper points at critical points on the PCB would have proved a simpler and less tedious process. This was evident in the malfunctioning of the voltage regulator.

A voltage regulator was not necessary in the circuit design. The battery life of the power supply is sufficient for one not to be concerned with regulating voltage at the input to the subsystem.

Careful consideration needs to be taken when placing footprints in the design of the PCB to ensure that the sensors are placed in the correct sensing direction. This would have prevented the unnecessary damage to components that were initially mounted on the PCBs.

The above recommendations would have thoroughly improved not only the PCB itself, but the time taken to rectify the errors made upon the initial arrival of the PCBs.

Chapter 6

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