The University of Manchester

Department of Electrical and Electronic Engineering

Embedded Systems Project 2023-24

Proposal Document

Group Number: 48

Group members:	ID Number	I confirm that this is the group's own work.
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Date: 09/02/2024

Contents

1. Introduction, Aims and Objectives

The aim of this project is to develop a quick and robust buggy that can follow a white line with various challenges on track. This project requires carefully planning and testing to make well-informed decisions. The technical side requires knowledgeable and skilled engineers to develop and integrate multiple different areas. This means the team must communicate and collaborate effectively to ensure the best results.

This proposal report outlines the main technical disciplines that are involved in the engineering design, how the team is organised and the timeline we will be using to plan and track progress.

Throughout the project, extensive research and testing were conducted to inform the technical decisions made for the buggy. This covered all critical technical elements, such as the electrical configuration, software design, control algorithms, and the physical design of the buggy. The processes used for the integration of these components into the final buggy are further detailed in this report.

In order to ensure all parts of the design, test and build process is completed to a high level, the team must establish standards for decision making, communication, task allocation and information sharing. The approached used and learning points for the upcoming semester are reflected upon.

The planning and budget of the project is also discussed in detail. Monitoring progress will ensure we are on track to complete and test the buggy within the deadline. The main milestones that we will be tracking the progress of are the technical demonstrations (TDA, TDB, Heats), final race, PCB design, laser-cut design, design document and final report submission. Finally, the buggy's total cost is calculated including with the planned budget spending for the winning features.

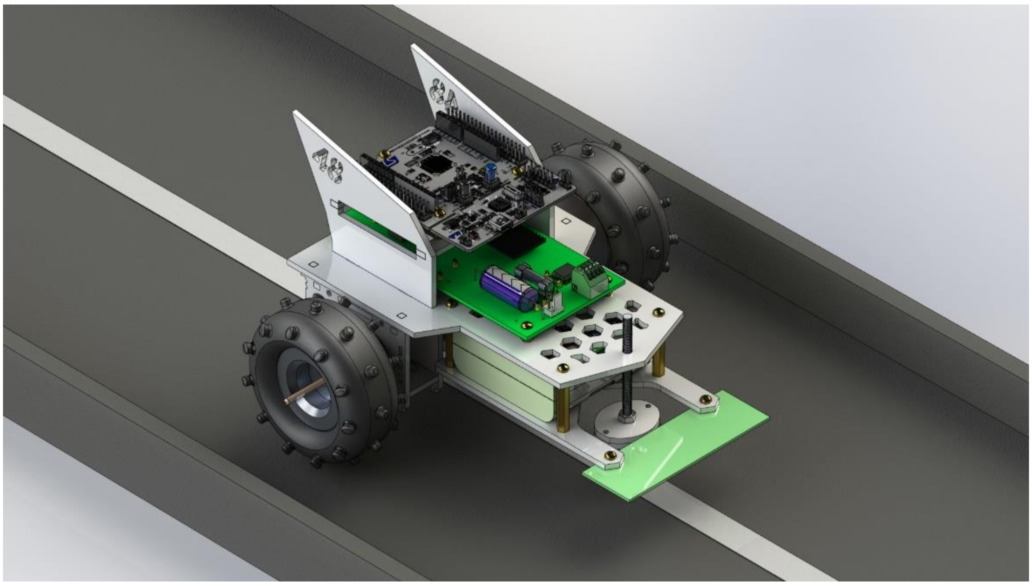


Figure 1.1: The buggy 3D render.

Figure 1.1 presents a 3D rendered image of the buggy, created using SolidWorks to showcase the result of careful design considerations. The CAD model provides a detailed visual representation, highlighting key aspects such as the strategic battery placement and hexagonal pattern on the chassis.

2. Technical Overview

The Technical Overview section encapsulates a comprehensive summary of the various components and methodologies that underpin the design and operation of the autonomous buggy. This section delves into the intricate processes of motor characterization, sensor selection and characterization, software system design, control algorithms, chassis design, and innovative features that collectively contribute to the buggy's competitive edge. Additionally, it also underscores the interconnectivity and interdependence between each design aspect.

2.1. Motor Characterisation

The motor characterization for the buggy was driven by the objective to move up an 18-degree slope. This required rigorous testing of the motor to determine its electrical and mechanical characteristics, specifically the torque constant, back EMF constant, armature resistance and brush voltage. These parameters were meticulously calculated and estimated from data obtained through three different tests.

Subsequent testing was focused on assessing the buggy's friction to find the minimum torque necessary for it to ascend the slope. It was found that the current required for the motor to produce sufficient torque for the climb exceeded feasible limits, indicating that the motor alone could not meet the performance criteria.

To resolve this, the use of a gearbox was deemed essential. Gearbox 2 with a 15:1 gear ratio, was selected. This specific gearbox was estimated to provide just enough torque to ascend the incline with the minimum speed reduction. A higher gear ratio was considered but ultimately not chosen, as it would have excessively reduced the buggy's speed.

Another crucial outcome from the motor and gearbox testing was determining the optimal speed for the buggy to climb the slope under a constant voltage while avoiding overcurrent which is 0.585 m/s. This speed value is integral to the buggy's control system as it provides the value for the control algorithm's constant set speed.

Maintaining a constant speed is essential, setting the speed too high during ascent risks overcurrent and overheating the motor. One way to mitigate this, a current sensor on each motor serves as feedback, triggering a slowdown when the safe current threshold of 1.4 A is approached. However, this solution introduces a challenge during descent. With the motors drawing less current, combined with the force of gravity, the buggy could accelerate beyond safe limits and potentially crash.

Therefore, maintaining a constant speed is considered vital. The specific value for this speed, 0.585 m/s, becomes a key input for the control algorithm. Without a constant speed setting and without any feedback to indicate a downward slope, the buggy faces a risk of uncontrolled descent. Addressing this issue is the objective of one of the winning features, aiming to equip the buggy with the necessary feedback system to adapt its speed on varying inclines automatically.

2.2. Sensor Characterization

Sensors are vital in making the buggy to move in a controlled manner since it will provide necessary feedback to the microcontroller which be used to calculate the appropriate control signal to the motors. Further elaboration on the application of each sensor within the control algorithm will be provided in the following section. The buggy’s control algorithm will incorporate four primary sensors:

1. A line sensor array to determine the distance from the centre of the line, which is crucial for maintaining the buggy's path.
2. Encoders (AEAT- 601B-F06) on each wheel to measure the rotational speed, providing data for speed regulation and distance travelled.
3. Current sensors (ACPL-C78A-000E) on each motor to ensure the motors operate within safe parameters and prevent overcurrent.
4. Bluetooth module (HM-10) to receive the command initiating a U-turn.

In the selection of line sensors, three different models were evaluated through a series of tests to gauge their performance under various conditions. Different biasing resistors were also experimented with to optimize the sensors' output. Ultimately, the TCRT5000, paired with a 100Ω resistor, was chosen. It offers the best performance and a smooth line spread function, enabling the derivation of distance from the voltage output. A valuable feature of the TCRT5000 is its built-in daylight filter, which significantly reduces the impact of external lighting conditions, enhancing sensor reliability.

Moreover, the TCRT5000 sensor's sensitivity is adjustable by altering its height from the track. After rigorous testing, a height of 15 mm was determined to be optimal for the analogue output setup. This configuration ensures a smooth voltage output corresponding to the distance from the line, which can be accurately read by the STM32's ADC. In an alternative setup, utilizing the sensor's digital output, a height of 10 mm was identified as ideal. At this lower height, the sensor provides a sharp, linear voltage drop at the transition from the white to the black part of the track, which is beneficial for precise digital line detection. This flexibility in sensor setup allows for customization if a different configuration is needed in the future.

An array of five TCRT5000 sensors is strategically positioned on a PCB, with each sensor playing a crucial role in determining the buggy's position relative to the centre of the line. To effectively derive the position from these sensors, a weighted average formula is employed. This formula calculates the distance from centre, d, which serves as a crucial feedback input for the control algorithm. The formula is shown below:

$$d = \frac{\sum_{i=1}^{n} V_i \cdot x_i}{\sum_{i=1}^{n} V_i} \qquad (2.2.1)$$

Where x_i is the individual weight of each sensor depending on their position in which the farthest ones have the highest weight. V_i is the individual sensor voltage output and n is the number of sensors, which is 5 in the current configuration.

The integration and functionality of the encoders in the buggy's design are essential for effective speed control. The chosen encoder, AEAT-601B-F06, is interfaced using the timers on the STM32 microcontroller. Capable of producing 1024 counts per revolution, this encoder provides detailed data on the wheel's rotational movement.

By measuring the number of counts within a specified time duration, the encoder allows for the precise calculation of the wheel's rotational speed in RPM (Revolutions Per Minute). This RPM data becomes a critical component of the motor's PID control system as feedback, enabling the regulation of the Pulse Width Modulation (PWM) signal's duty cycle. Adjusting the PWM duty cycle in response to the RPM feedback ensures that the buggy's speed is controlled accurately, maintaining the desired speed set by the control algorithm, and contributing to the overall stability and performance of the buggy.

2.3. Software System Design

In the development of the buggy's software, we opted for the Mbed framework in C++ due to its balance between ease of use and robust programming capabilities. While this decision implies a trade-off in terms of accessing lower-level controls, the benefits are substantial. Mbed abstracts many of the technical intricacies, allowing for a more rapid development cycle and significantly reducing the risk of bugs that often occur when configuring lower-level details manually.

The use of C++ as the programming language brings the advantage of object-oriented programming (OOP). This approach is vital in structuring our code efficiently. We have harnessed the power of OOP to create three primary classes: Motor, Control, and Sensor. These classes enable us to manage the complex functionalities of the buggy in an organized manner, with each class responsible for distinct yet interrelated aspects of the system.

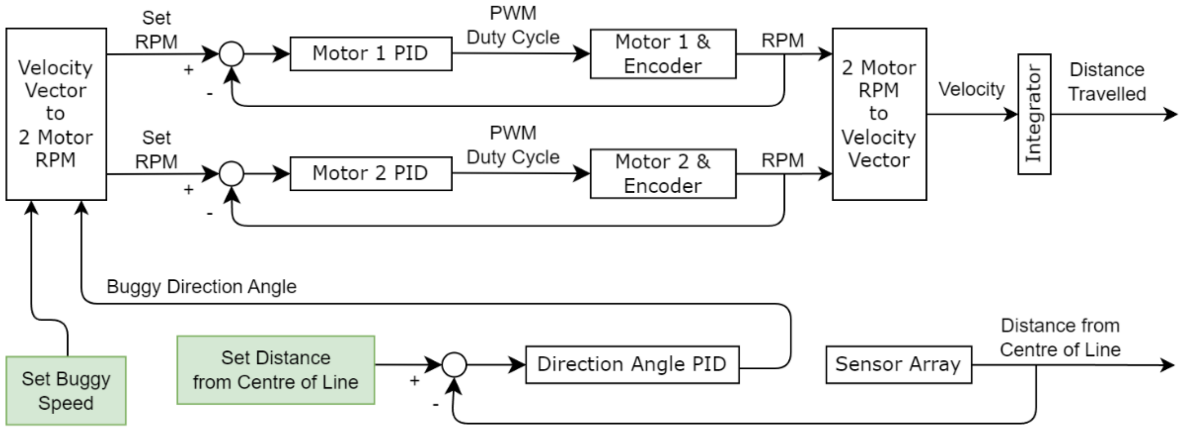


Diagram 2.1: Buggy Control Flow Overview

The high-level control flow of the autonomous buggy is designed to enable it to follow a line independently, without external commands. As depicted in Diagram 2.1, the control algorithm receives only two inputs: the set buggy speed and the set distance from the centre of the line. The distance is ideally zero to align the buggy with the line, while the set speed is constant, determined by the maximum speed the buggy can maintain on an 18-degree ramp without overcurrent, as discussed in the previous section.

The buggy's direction is regulated by a Discrete PID (Proportional-Integral-Derivative) control algorithm, which adjusts based on feedback from the sensor array. The computed set speed and direction angle combined to form a velocity vector, which is then translated into the RPM required for each wheel to attain the desired velocity. This set RPM is fed into a Motor PID controller, which takes feedback from the encoders. The controller's output, a PWM duty cycle, is sent to the motor driver board to regulate motor voltage. Subsequently, the RPM readings from both encoders are converted into velocity and integrated to determine the distance travelled by the buggy. Each block in the diagram represents an object or function to be implemented, ensuring an organized relationship between system components.

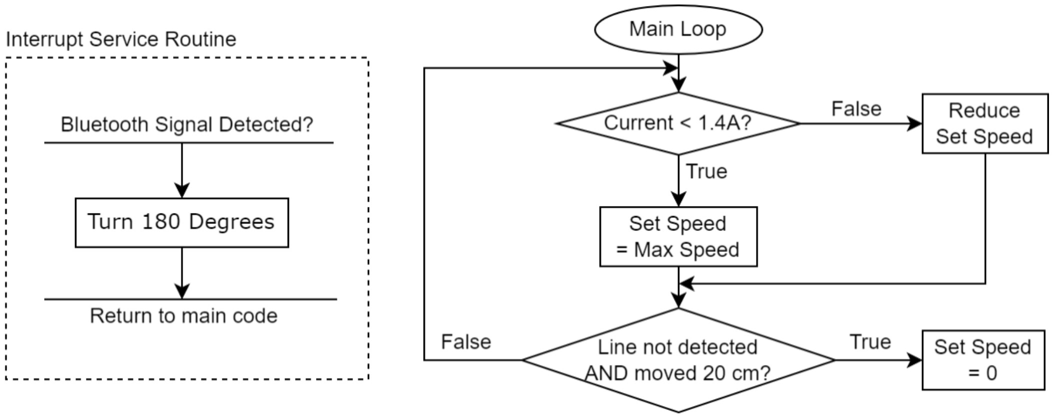


Diagram 2.2: Main Program Overview

The control flow algorithm accounts for the buggy's basic movement but requires additional considerations for other objectives. Therefore, another higher-level main program will control the buggy's set speed and take care of the other special cases.

For instance, to achieve a 180-degree turn upon receiving a Bluetooth command, interrupts are utilized for a swift response, bypassing continuous polling. Additionally, as a safety measure, an overcurrent protection is implemented to prevent damage to the motor driver board in the event the buggy becomes stuck. Finally, the main loop continuously checks for line detection, with the buggy programmed to halt if the line is not detected for 20 cm. This control strategy ensures that the buggy not only follows its path effectively but also responds promptly to special cases and safeguards its electronic components.

2.4. Control Algorithms Selection

The selection of the Discrete PID algorithm for controlling the buggy was a strategic decision, driven by the need for precision and stability. The Bang-bang control approach was considered unsuitable due to its binary, all-or-nothing response, which can lead to instability and inefficiency in control.

The PID algorithm, in contrast, offers a more nuanced control mechanism. The Proportional (P) component ensures reliable control but can lead to oscillations. The Integral (I) part addresses this by eliminating steady-state error, effectively smoothing the response over time. The Derivative (D) component adds dampening, which helps to counteract the overshooting and reduces oscillations. However, the D component is susceptible to noise, necessitating the inclusion of a digital low-pass filter for the error input in code to mitigate this effect.

The PID algorithm will be implemented in code based on this equation:

$$u(t) = K_p \cdot [e(t)] + K_i \cdot \left[\sum_{\tau=0}^{t} e(\tau) \cdot \Delta t\right] + K_d \cdot \left[\frac{e(t) - e(t-1)}{\Delta t}\right] \qquad (2.3.1)$$

Where $u(t)$ is the control output at time t. K_p, K_i, K_d are the proportional, integral, and derivative gains, respectively. $e(t)$ is the error at time t and Δt is the time interval between samples.

Due to the complexity of implementing all three components (P, I, and D) simultaneously, there might be a phased approach in its implementation. Initially, the Proportional control could be implemented and tuned, followed by the gradual integration of the Integral term and then the Derivative term. This stepwise approach allows for thorough testing and fine-tuning of each term's gain constant, ensuring optimal performance and stability in the buggy's control system.

2.5. Chassis Design

The design of the buggy involved meticulous choices to optimize its performance and functionality. One such choice was the placement of the battery below the main chassis to lower the centre of gravity. This strategic placement enhances the buggy's stability, particularly in manoeuvring at sharp corners. Additionally, the chassis features a hexagonal pattern of holes, serving a dual purpose: weight reduction and efficient cable management routing. This design not only lightens the buggy but also simplifies the internal layout, leading to improved ease of maintenance.

Another key design element is the positioning of sensors at the front of the buggy, with their height adjustable using screws. This adjustability allows for fine-tuning sensor sensitivity, thereby improving the buggy's responsiveness. Moreover, the electronic boards are stacked at the back, a decision aimed at minimizing wire length. This arrangement leads to a more organized and compact design, reducing the potential of misrouting the wires during assembly.

Material selection is another critical aspect of the design process. Four different materials were considered and evaluated based on six performance criteria. After thorough consideration, acetal was selected for its optimal balance of properties. A thickness of 3mm was determined to offer the best strength-to-weight ratio, as concluded from Finite Element Analysis (FEA). This choice of material and thickness underscores the emphasis on achieving a robust yet lightweight design, crucial for the buggy's performance and durability.

2.6. Winning Features

To gain competitive advantage, a revision in the buggy's speed control system was identified as necessary. Under the existing configuration, the buggy maintains a constant speed, set based on the maximum speed it can sustain on an 18° incline without overcurrent (1.4A), and to prevent excessive speed on descents. This results in suboptimal performance on flat parts of the track, as the buggy operates well below its current limit due to the imposed speed restriction.

The first winning feature tries to address this problem by incorporating a 3-axis accelerometer. This sensor will allow for tilt angle detection relative to the gravity acceleration vector. With this data, the buggy's speed can be dynamically adjusted. On flat surfaces, the maximum speed will be increased, utilizing the available current without overcurrent risk. On inclines, the speed will be proportionally reduced based on the tilt angle. This approach ensures the buggy maximizes its speed potential on flat parts of the track while preventing overcurrent risk while on ramps.

The second winning feature further optimizes the buggy's performance on navigation and speed control. On straight sections, the buggy can accelerate rapidly, but as it approaches corners, it must decelerate in advance. To address this, the integration of a 9 Degrees of Freedom Inertial Measurement Unit (BNO085) with sensor fusion algorithm, coupled with encoder data, was proposed. This feature will enable the calculation of the buggy's absolute position on the track, allowing for pre-programmed speed profiles tailored to specific track segments, optimizing speed and stability.

The implementation of this feature is currently in development. The team is exploring options, including designing a program to map the track with associated speed profiles or allowing the buggy to record the track shape and automatically calculate the optimal speed profile on its initial run. However, this second feature, while ambitious, presents a higher risk of bugs and potential reliability issues. Thorough testing is essential for its successful integration.

3. Team Organisation

Working together as a team is essential for the group's success. Creating effective spaces for communication and sharing ideas, assigning roles that align with each member's strengths, setting standards for each member's contribution and establishing a decision-making process all contribute to the team's ability to meet its aims and objectives. The way the team achieved this will be discussed in this section, as well as reflections on how this can be improved next semester.

3.1. Roles and Responsibilities

Individually, all team members understand they have a common responsibility towards this project's success. The team is structured around mutual accountability and respect. When a member is struggling with their task any other member can step in to support them and similarly where a member is falling behind schedule any other member can remind them. When determining specific roles for assignment, members who have previous technical experience or an interest in a certain area volunteer, and others who are more flexible fill in the remaining tasks. For example, a team member who had previous experience with CAD software volunteered to design the chassis and another who had programming expertise completed the software section. Using everyone's strengths and interests maximizes the team's productivity, whilst individual flexibility ensures nothing is overlooked. Each week a different member completes the journal summary to ensure everyone is involved and up to date with the project progress.

3.2. Communication and Collaboration

The main channel for communication within the team is the WhatsApp group chat. Meetings are arranged using this group chat, members can give updates on the task's progress, ask for feedback or suggestions from other teammates and resolve issues quickly. This has proven to be an efficient way of discussing ideas and providing feedback. The team meets regularly after each weekly tutorial to discuss the week's agenda and plan checkpoints for the coming week. Extra meetings have been arranged around the team's availability for things such as discussing lab results, exploring PCB/CAD designs, analyzing graphs, and drawing conclusions from them, checking calculations and scrutinizing the final report draft. Throughout these meetings, members are encouraged to be critical of each other's work and open-minded to changes. Significant decisions such as assigning tasks and design approaches are made during these meetings with the consensus of all members of the team. So far, all decisions have been made in this way, disagreements have been resolved through open team discussions to ensure everyone's opinion is considered and all are satisfied with the approach taken.

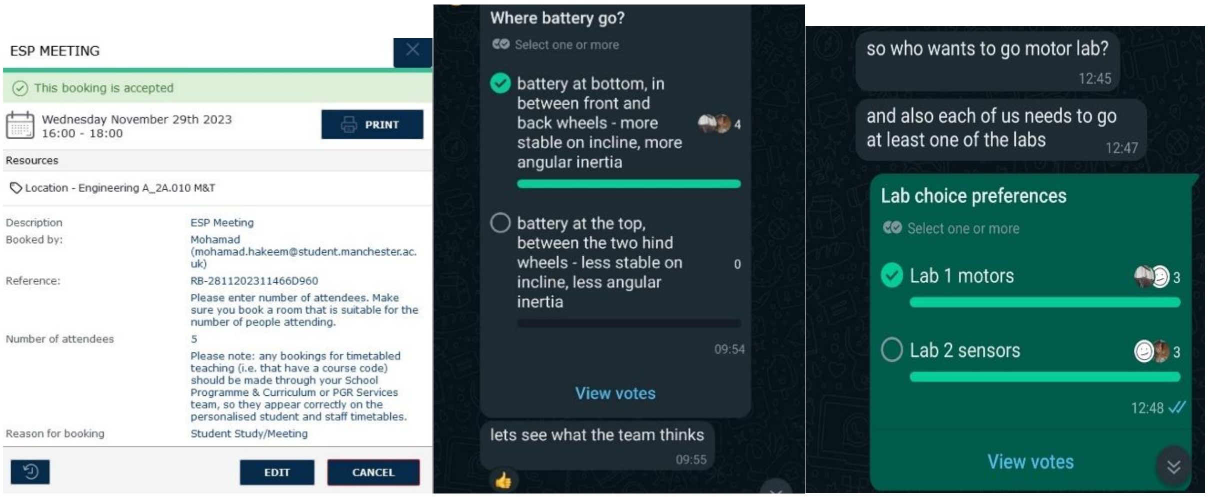


Diagram 3.2.1 Example meeting room booking, WhatsApp group discussions.

3.3. Document Sharing

All team members have access to a shared OneDrive folder. As seen in the image below, there are individual folders for each report and lab where resources can be shared. Before each lab, a shared excel sheet was prepared so everyone could access the data and graphs. In the main shared report word document, each team member was assigned a section for which they were responsible, suggestions and changes by others were placed in comments, highlighting the part that should be replaced. Where the responsible member did not agree with change, it was discussed in the following meeting. This was to ensure that nothing was removed or deleted without the author's knowledge. For software the team will be publishing to a GitHub repository from Keil studio. This is for everyone to collaborate and test the code individually. A Trello Board was used to track progress on tasks and keep a record of contributions.

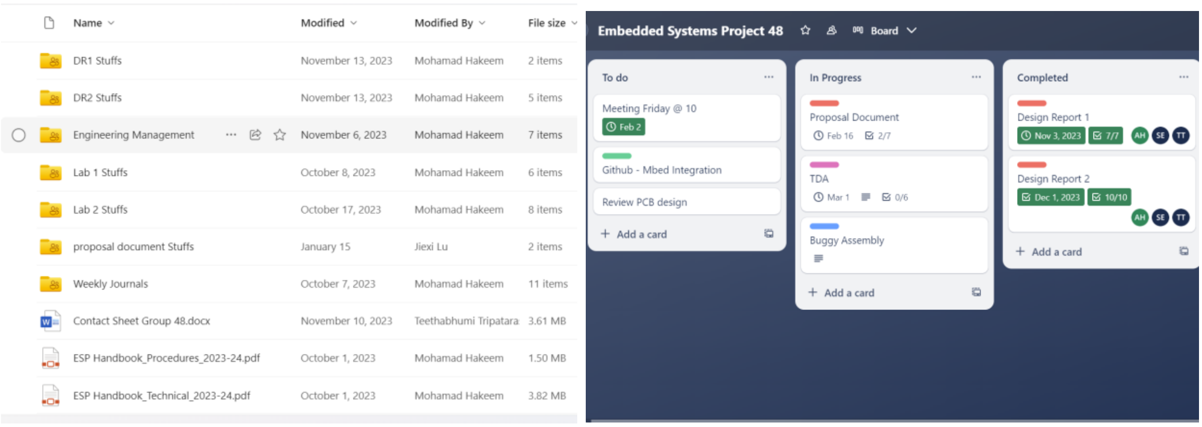


Diagram 3.3,1: Team's OneDrive (Left) and Trello Board (Right)

3.4. Learning Points for Next Semester

Overall, the current strategy seems to be working well but there will be some significant changes that need to be made for next semester. As the rest of the project will be more hands-on, meetings will need to be more frequent to prototype, test and build. One challenge will be clashing timetables and availability, to prevent delays individuals or pairs can work on the prototyping or testing the buggy. The Trello board will be more extensively to track tasks and to split the workload. Overall project progress will be monitored using our Gannt chart.

An incident that we reflected on as a team was related to formatting inconsistencies in a design report. This was not picked up until close to the deadline, this led to panic and last-minute changes. To ensure this does not happen again, for all following reports a member of the team (alongside their other contributions) is assigned to monitor the format and length of the report. This will mean that the report is formatted correctly as we go.

4. Planning and Budget

When planning for the project, the team decided that it would be best to refer to the Semester 2 timetable schedule on the ESP Handbook Procedures PDF available to all the students since within the timetable are the deadlines of submissions and dates of demonstrations which are the deliverables. Below are the dates of important deadlines and deliverables:

Event	Date
PCB Submission	12/04/2024
TDA	01/03/2024
Design Document Submission	12/04/2024
TDB	19/04/2024
Laser-Cutting & Order Submission	19/04/2024
Heats	30/04/2024
Race	02/05/2024
Final Report	10/05/2024

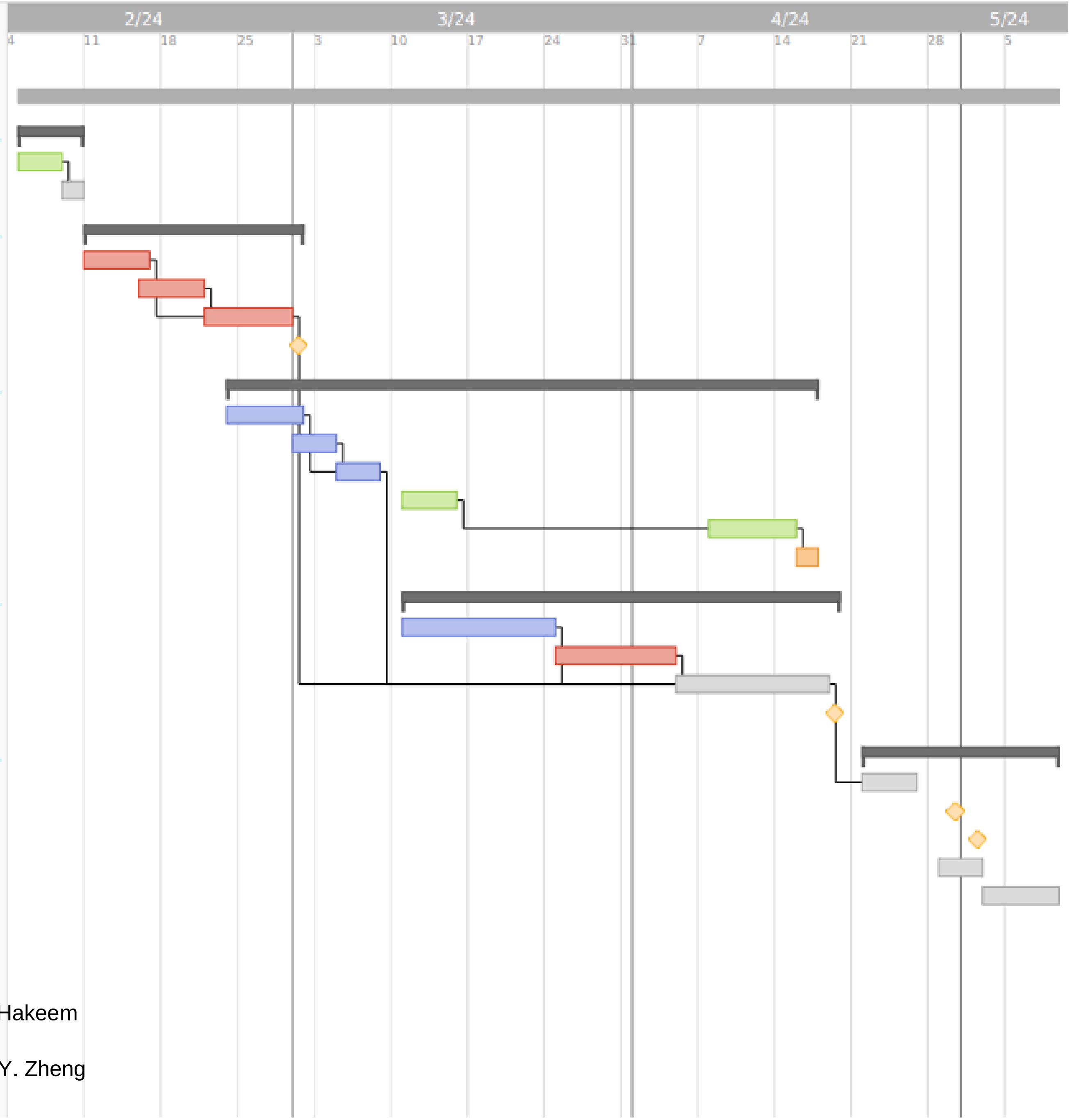
Table 4.1: Important Dates

Therefore, the team decided to use these dates as the basis for the Gantt chart with the activities associated with the respective deadlines being completed before the deadline time.

All the physical aspects such as soldering and buggy assembly will be done in the lab together. This is to make sure everyone knows and understands the hardware, which would help in developing the software. As of now, the team devised that for software development, the program will be written and shared in GitHub. The code will also be properly commented to explain what each variables represent and what each section does so that everyone will understand and can work on top of the existing code with as little confusion as possible. In the lab, the code will be tested, and lab time will generally be for debugging the code and testing the program on the buggy. This means that to make the most out of lab times, the first rendition of the code should be written already rather than writing a brand-new code in the lab.

Should any member feel like they want to continue at their own abode individually, they will take the buggy with them and continue the work. The priority will be given to the person coding on the main function which integrates all the objects together and would need the buggy to check that everything works together smoothly. After lectures, the buggy can be swapped around if necessary for other team members to work with, since labs are once or twice a week.

Semester 2	start	end
Buggy Prototype	**05/02/24**	**10/02/24**
Prototype of Sensor Array	05/02	08/02
Assembly of Buggy Prototype	09/02	10/02
Motor Control	**11/02/24**	**01/03/24**
Motor Class Development	11/02	16/02
Software Development PWM	16/02	21/02
Implementation within Main Code	22/02	29/02
TDA	01/03	01/03
Sensor Implementation	**24/02/24**	**17/04/24**
Sensor Class Development	24/02	01/03
Non-line Sensors Class Development	01/03	04/03
Implementation within Main Code	05/03	08/03
Sensor Array PCB Design	11/03	15/03
Solder and Assembly of PCB	08/04	15/04
Substitute Prototype Circuit for PCB	16/04	17/04
Steering Control	**11/03/24**	**19/04/24**
PID Class Development	11/03	24/03
Bluetooth ISR Development	25/03	04/04
Main Function Code Development	05/04	18/04
TDB	19/04	19/04
Presentation	**22/04/24**	**09/05/24**
Heats & Race Preparation	22/04	26/04
Heats Day	30/04	30/04
Race Day	02/05	02/05
Peer Review Form	29/04	02/05
Final Report	03/05	09/05



= S. El - Mahmoudi

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= J. Lu, M. A Hakeem, S. El - Mahmoudi, T. Tripatarasit, Y. Zheng

MANCHESTER 1824

The University of Manchester

WORK ACTIVITY/ WORKPLACE (WHAT PART OF THE ACTIVITY POSES RISK OF INJURY OR ILLNESS)	HAZARD (S) (SOMETHING THAT COULD CAUSE HARM, ILLNESS OR INJURY)	LIKELY CONSEQUENCES (WHAT WOULD BE THE RESULT OF THE HAZARD)	WHO OR WHAT IS AT RISK (INCLUDE NUMBERS AND GROUPS)	EXISTING CONTROL MEASURES IN USE (WHAT PROTECTS PEOPLE FROM THESE HAZARDS)	WITH EXISTING CONTROLS			
					SEVERITY	LIKELIHOOD	RISK RATING	RISK ACCEPTABLE
Inspecting the racetrack	Tripping on the racetrack	Part of the racetrack is ruined, and the person is hurt physically	The person who tripped and injured themselves	Keep a safe distance between yourselves and the track as well as being spatially aware Refrain from crossing around the track too often	1	1	1	Yes
Inspecting buggy after performance	Hot motors	slight pain to the touch	The person inspecting the buggy	Leave the buggy to cool for a while and avoid immediately touching the motor	1	2	2	Yes
Having bottled beverage at the venue	Liquids spilling onto and into the electric plugs at the venue	Loss of power and electrically shocking the people using and/or working that socket	The person or group utilising that socket	Keep drinks away from any electrical sockets and electronics Keep the drinks limited to only water as to not leave residue	5	1	5	Yes
Buggies colliding with obstacles at high speeds or crashing into a person	Injury to foot	Causes minor abrasions and, in the case of sharp objects, may cause severe abrasions	The person close to the track	Use softer materials to build the edges of the track. people should keep a safe distance from the track during the race	1	2	2	Yes

Assessment ID Number (E&EE_Initials_DATE_Number)...............N/A.......................... **Activity Location:…………Whitworth Hall ……………………**

				THIS RISK ASSESSMENT WILL BE SUBJECT TO A REVIEW NO LATER THAN: (MAX 12 MTHS)
MANAGER/SUPERVISOR	NAME: Wuliang Yin	SIGNED: Wuliang Yin	DATE: 05/02/2024	
Student:	NAME: Teethabhumi Tripatarasit	SIGNED: Teethabhumi	DATE: 04/02/2024	

IF THE ANSWERS TO ANY OF THE QUESTIONS BELOW IS YES THEN ADDITIONAL SPECIFIC RISK ASSESSMENTS MAY BE REQUIRED.

IS THERE A RISK OF FIRE?	Y/N	DOES THE ACTIVITY REQUIRE ANY HOME WORKING?	Y/N
ARE SUBSTANCES THAT ARE HAZARDOUS TO HEALTH USED?	Y/N	ARE THE EMPLOYEES REQUIRED TO WORK ALONE	Y/N
IS THERE MANUAL HANDLING INVOLVED?	Y/N	DOES THE ACTIVITY INVOLVE DRIVING	Y/N
IS PPE WORN OR REQUIRED TO BE WORN?	Y/N	DOES THE ACTIVITY REQUIRE WORK AT HEIGHT	Y/N
ARE DISPLAY SCREENS USED?	Y/N	DOES THE ACTIVITY INVOLVE FOREIGN TRAVEL	Y/N
IS THERE A SIGNIFICANT RISK TO YOUNG PERSONS?	Y/N	IS THERE A SIGNIFICANT RISK TO NEW / PREGNANT MOTHERS?	Y/N

Severity value **= potential consequence of an incident/injury**

5 Very High Death / permanent incapacity / widespread loss

4 High Major Injury (Reportable Category) / Severe Incapacity / Serious Loss

3 Moderate Injury / illness of 3 days or more absence (reportable category) / Moderate loss

2 Slight Minor injury / illness – immediate First Aid only / slight loss

1 Negligible No injury or trivial injury / illness / loss

Likelihood value **= what is the potential of an incident or injury occurring**

5 Almost certain to occur

4 Likely to occur

3 Quite possible to occur

2 Possible in current situation

1 Not likely to occur

risk rating = severity value* × *likelihood value

risk ratings **are classified as *low* (1 – 5), *medium* (6 – 9) and *high* (10 – 25)**

Risk Classification and Actions:

Rating	**Classification**	**Action**
1 – 5	Low	Tolerable risk - Monitor and Manage
6 – 9	Medium	Review and introduce additional controls to mitigate to “As Low As Reasonably Practicable” (ALARP)
10 – 25	High	Stop work immediately and introduce further control measures

SEVERITY

LIKELIHOOD	1	2	3	4	5
1	Low	Low	Low	Low	Low
2	Low	Low	Medium	Medium	High
3	Low	Medium	Medium	High	High
4	Low	Medium	High	High	High
5	Low	High	High	High	High

Item	Description	Part No.	Supplier	Qty	Unit Price (£)	Cost (£)
Mechanical Parts						
Acetal Sheet	(600 x 900 x 3 mm) for chassis	-	UoM	1	42.00	42.00
Front Wheel	Ball Castor	955	Pololu	1	4.01	4.01
Rubber Tyre	80 mm Spiked Tyre	06-0654	Rapid	2	1.45	2.90
Motor	6-15V 8W DC Brushed	238-9737	RS	1	6.61	6.61
Gearbox Box	Acetal box + gears	-	UoM	1	7.00	7.00
Integrated Circuits						
MCP6004	Quad 1 MHz, Op Amp	403-181	RS	1	0.64	0.64
LM339	Quad Comparator	533-8237	RS	1	2.02	2.02
ULN2003	7 Element Darlington	686-8209	RS	1	0.66	0.66
Sensors						
TCRT5000	Reflective Optical Sensor	818-7524	RS	5	0.72	3.60
AEAT-601BF06	Broadcom encoders	2467469	Farnell	2	21.40	42.80
HM-10	Bluetooth Module	RB-Suf-03	RobotShop	1	13.53	13.53
Populated PCBs						
NUCLEO-F401RE	STM32F401RE Nucleo Dev.	NUCLEO-F401RE	Avent	1	15.00	15.00
MBED-016.1	Mbed Application Shield	2468119	Farnell	1	42.54	42.54
STM breakout	STM32 Break out board	Proprietary	-	1	10.00	10.00
Controller Board	Motor Drive Board	Proprietary	UoM	1	30.00	30.00
Misc						
Battery Holder	Custom with fuse, 8-way	3829583	Farnell	1	2.28	2.28
Batteries	AA, 1.2 V, Rechargeable	617-0773	RS	8	2.70	21.60
Insulation Tape	19 mm tape (white)	227-2976	RS	1	2.56	2.56
Resistors	Through Hole Carbon Film Resistor	Various	RS	12	0.10	1.20
Screws	Steel M3 Screws (Various Heights)	Various	RS	8	0.08	0.64
Nuts	Steel M3 Nuts	189-563	RS	8	0.07	0.56
Standoffs	Steel M3 Standoffs	Various	RS	8	0.20	1.60
Red Wire	1m, 7/0.2 mm, Hook Up Wire	207-5298	RS	2	0.15	0.30
Black Wire	1m, 7/0.2 mm, Hook Up Wire	207-5297	RS	2	0.15	0.30
Yellow Wire	1m, 7/0.2 mm, Hook Up Wire	196-4234	RS	2	0.14	0.28
					Total Cost (£):	**254.63**
Budget Spending						
BN0085	9 DOF IMU Breakout Board	-	Pimoroni	1	27.00	27.00
				Total Cost (£):		**27.00**
				Contingency (£):		**13.00**

Table 4.2: Parts cost list with planned budget spending.

5. Summary

This report outlines a detailed plan to construct a reliable white line following buggy, focusing on the technical design, team roles, and project management.

The technical overview explained the configuration of motor and sensors used such as speed, voltage, and positioning supported by experimental data and careful design considerations. This is complemented with the chosen software system design with PID control algorithm to create a highly reliable buggy.

The team structure is designed to optimize project execution, with clear delineation of roles and a proactive approach to communication, leveraging modern platforms for collaboration. Record-keeping and decision-making protocols are in place to foster transparency and accountability.

The planning and budgeting frameworks are meticulously drafted to address potential challenges, with contingency plans to navigate uncertainties. The Gantt chart reflects the commitment to stay on schedule, while the parts list accounts for the costs of all components in order to manufacture the buggy.