The University of Manchester

Department of Electrical and Electronic Engineering

Embedded Systems Project 2022-23

Final Report

Title: White-Line Following Buggy

Group Number: 4

Group members:	ID Number	I confirm that this is the group's own work.
Asim Zubair	10541694	☒
Doruk Tan Atila	10866352	☒
Muhamad Muhamad Asri	10915564	☒
Muhammad Bin Suratman	10869503	☒
Zhixin Chen	10816322	☒

Tutor: Dr. Laith Danoon

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1.1. Executive Summary

A race to find the fastest buggy was carried out in the Embedded Systems Project for Academic Year 2022-2023. The buggy needed to dash through the completed track with different elevations and obstacles, all by following a white line across the whole track. This should be accomplished by the group through structured planning according to all specifications made by the course unit coordinator.

The buggy made by Group 4 was built with extreme care and rigorous brainstorming. A lot of requirements were made to ensure the buggies selected for the final race were of satisfactory qualities, and failure to comply with these would result in disqualification. Fulfilling all these stipulations required the buggy to churn enough torque to climb the ramp without compromising its average speed. For this, the second gearbox combination was deemed the best at both for the buggy. The sensors for the line following algorithm were also chosen carefully by plotting line spreads and checking their ambient noise likelihood. As per the results, six TCRT 5000 were chosen to pilot the buggy because of its sensitivity and accurate readings.

There were four main software algorithms piloting the buggy, including the sensor reading algorithm, encoder reading algorithm, speed and direction control algorithm, and Bluetooth control algorithm. These software parts were written modularly to allow any team members to improve the code and to ease any debugging process. All these software algorithms work in tandem in the PI (Proportional and Integral) and PD (Proportional and Derivative) controls. The group had to restrain from using the PI control, however, as time was very limited. This constraint was restricting the group from polishing the buggy to its full potential as they had to race against time to fine-tune the constants of the control system.

The group was aiming to increase their knowledge and skills in working as a team, and if possible, to achieve a successful run of the heats. To aid this objective, efficiency was crucial. In order to maximize efficiency and organise resources accordingly, the group produced a Gantt chart in the initial process of designing the buggy. The Gantt chart certainly did help, but it was not absolute. Multiple changes happened to the chart, most of which during the second semester of the academic year. The group had to improvise their hardware through last-minute testing and discussions. Only replacement of the resistor pair for the sensors was possible to allow good line following control: from 55 Ohm and 10k Ohm to 120 Ohm and 4k7 Ohm.

This sensor resistor combination and the control algorithm allowed the group to carry out a satisfactory initial run during the heats. The speed of the buggy had to be decreased notably, and this allowed the buggy to follow the line through the tracks without visible large oscillations. Some notable features of the buggy were its ideal size for turnaround on the track, its low centre of gravity preventing any flipping, and its source code which allowed easy alterations of constants.

All these hardware components cost the group an overall price of £268.81. This was £0.42 higher than the expected expense, but still within the budget. Provided mass production of this buggy was possible, this cost could be brought down significantly to £230. A proposed price point of £290 for the buggy could then allow a sufficient profitable margin for the business.

The team was extremely proud of their achievements in this project and were confident that their teamwork has and will improve should the project be repeated. Each group member overcame difficulties with all the deliverables, but each deliverable was achieved with more than satisfactory results.

1.2. Introduction

The purpose of this report is to conclude the buggy project for Group 4 of the Embedded Systems Project. The completed buggy is shown in Figure 1, and each component that was used to build the buggy, discussed in the next section, which is the components summary. The total components are then listed and calculated along with the actual cost of producing the whole functioning buggy in the budget vs outturn section. A comparison between the budget and the actual cost will also be briefed.

The buggy was required to be able to follow a white line of width 1.8 cm and to climb a sloped track of 18° maximum. Multiple tests were run on the hardware of the buggy before implementing the software and control algorithm. This was to ensure the buggy was not constrained by the hardware during the actual race. The implementation of the software then allowed the buggy to be piloted autonomously without any manual intervention. Each software was tested in chunks before compiling the whole control algorithm together. These tests will be discussed in the analysis of the heats section, where the buggy was required to complete the track according to the requirements stated earlier.

The hardware and software components used for this buggy were chosen after many discussions between each team member. The chassis and PCB were designed to fit each other perfectly as they held the base of the buggy. The sensors and other electronics choices also required a lot of considerations during the design period, which will later be discussed in the following section.

The finalised buggy, however, slightly differed from the initial expectations that the group had in mind. Each process in the assembly was included with its own impediment, but this was a mere inconvenience to the group as they managed to find a workaround for every one of them. The Team Organisation and Planning section shall explain this in detail. Furthermore, the cost had also changed from the budget calculation as a mistake in PCB design increased it by £0.42. This increase and the comparison between the budget and its actual cost will be briefed in the Budget vs Outturn section.

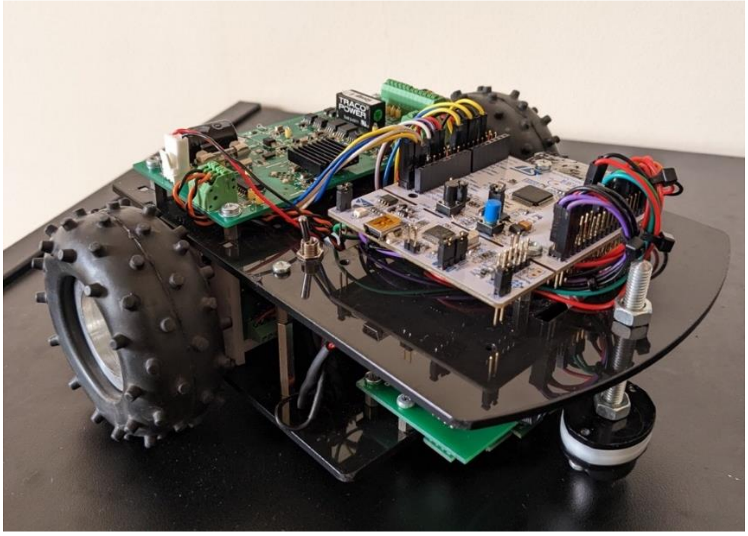

Figure 1 – Actual Photo of Finished Buggy

2. Final System Components Summary

2.1. Mechanical

During the early state of the Embedded System Project, the motors characterisation was performed which revealed that the motors lacked sufficient torque to enable the buggy to move up slopes. To address the issue, a gearbox was implemented to increase the torque on the wheels while sacrificing some speed to enable the buggy to climb the slope.

Table 1 – Available Gear Combinations [4]

Selection Number	Pinion Gear (motor shaft only)	Intermediate Gear Two common gears on one shaft	Gear on final drive
1	16 tooth	48/12 press fit gears (orange*)	48 tooth
2	16 tooth	50/10 press fit gears (orange)	48 tooth
3	16 tooth	50/10 press fit gears (red)	60 tooth

The project provided three different gearbox combinations to choose from, each with a different gear ratio, as shown the Table 1. To select the optimal gearbox, the force calculated should be greater than the load measurement, which was 6.302 N, the minimum torque necessary to climb slopes, the buggy's speed, and the current consumption were taken into consideration. During the labs, K_T which is the Torque constant for the stalled motor was measured at 0.0062 V/(rad/s), equalled to K_T for rotating which was 0.0064 V/(rad/s), while K_E, which is the back emf constant was 0.0062 V/(rad/s). Hence K_T and K_E were equal, and they were both constants. Using those parameters, the team derived the minimum current at 1.068 A for the required gearbox combination.

After careful calculations and group consensus, Group 4 decided to use the second gearbox combination which included 16 tooth for Pinion Gear (motor shaft only), 50/10 press fit gears (orange) for Intermediate Gear Two common gears on one shaft, and 48 tooth for Gear on the final drive.

2.2. Chassis

The design of the buggy's chassis played a crucial role in the Embedded Systems Project, as it served as the foundation for holding all the components together. It was imperative to keep the weight of the buggy to a minimum to increase battery life and velocity, while still ensuring that the chassis is sturdy enough to withstand the load of all the components. Acetal has the lowest density and is easy to laser cut, making it an ideal choice for the chassis.

Table 2 – Component Placement on Buggy

	Placement on Buggy	
	Front End	Rear End
Components	Battery Pack (265 g)	Motor + Gearbox + Encoder + Wheel (456 g)
	Nucleo-F401RE + UM1601 (108 g)	Motor Drive Board (53 g)
	Castor (30 g)	-
	Line Sensor PCB (≈40 g)	-
Total Mass	**443 g**	**509 g**

The placement of the components on the buggy was important, as it impacts the buggy's stability. From Table 2, it is important that the mass of the front components (443 g) and rear components (509 g) were equal for optimal weight distribution and should be positioned on opposite ends of the chassis. This ensured that the load is evenly balanced across the buggy.

2.3. Electronic

The autonomous vehicle designed by Group 4 for Embedded Systems Project is equipped with six TCRT 5000 sensors. TCRT 5000 sensors were highly effective due to their built-in compatible emitter and detector, direct daylight-blocking filter, and an infrared wavelength of 940 nm. As a result, TCRT 5000 sensors could be less affected by ambient sunlight compared with other sensors and able to provide accurate readings as the ambient sunlight belongs to visible sunlight rather than infrared [2].

Moreover, TCRT sensors are equipped with the most sensitive line spread function, which shows how much the sensor blurs the edge of the white line [4]. The optimal range of the reading was measured from -0.6 cm to 0.6 cm, ideal for the width of the white line. Hence TCRT 5000 could precisely detect whether the buggy was at the edge of the white line and respond to any deviation from the white line. Therefore, the buggy could keep following the white line and complete the track.

To ensure the accuracy of the sensors' reading, the sensors were modified and tested at various heights. It was determined that the optimal height for TCRT5000 sensors was 4 mm above the white line, which eliminated most influence from the reflectivity of the white line. Additionally, the sensors were positioned under the shadow of the upper chassis to avoid ambient sunlight interference.

Furthermore, the resistors used for connecting the emitter and transistor in TCRT 5000 sensors were adjusted a lot. Considering the reflectivity, the influence of ambient sunlight and the sensor reading, Group 4 decided to use TCRT sensors with 120 ohm and 4k7 ohm, which had the most sensitive reading under the 4mm gap to the track, showing 0.77 V in the dark area and 4.45 V above the white line.

After ensuring the optimal height and the resistors used with sensors, the next challenge was determining the number of sensors and their allocation. The finalised PCB had a dimension of 46.36 mm by 85.85 mm. The sensors were placed in the front of the buggy, with the two middle sensors placed 1.4 cm apart, just shy of the track line width of 1.8 cm. The sensors in the second and third rows were also placed 1.4 cm from the sensors in the previous row but at an angle of 0.9°, which aligned with the technical handbook [5] guidance on the final track design curvature “the white line will not change direction by more than 45° every 50 mm for an angle bend”.

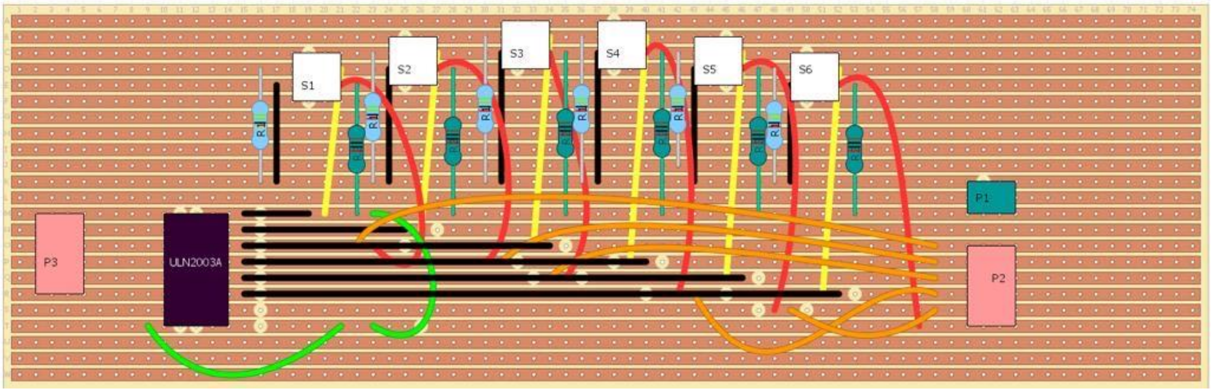

Figure 2 – Stripboard Layout

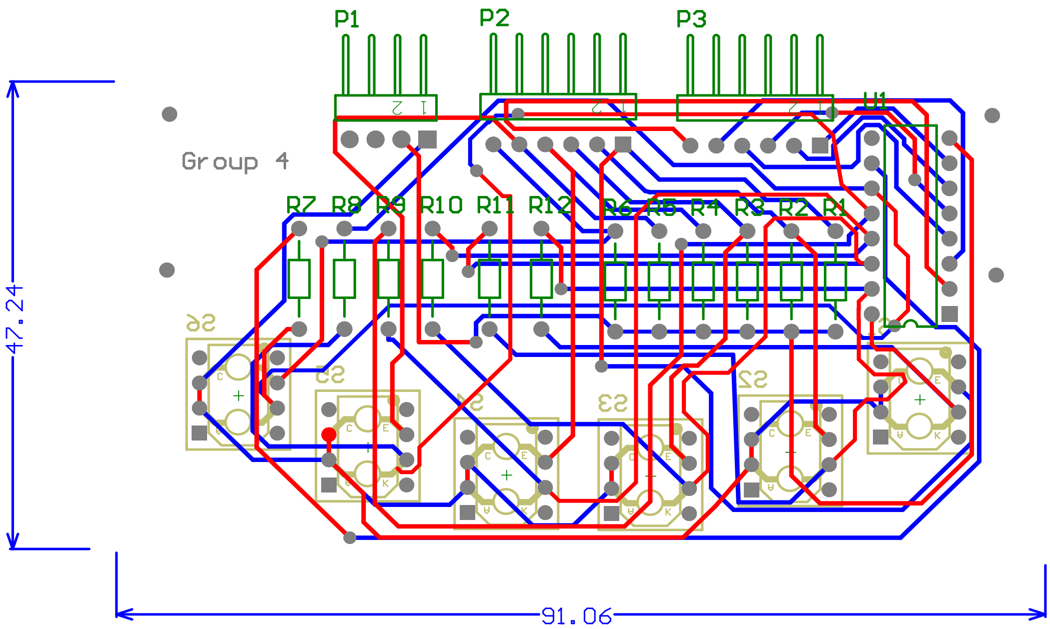

Figure 3 – PCB Layout

Six sensors were placed as the Figure 2 and 3 above. To ensure precision and accuracy, a PCB was used instead of a stripboard, as the latter’s fixed hole gaps might not align with the calculated sensor allocations. Meanwhile, the wire connection of the stripboard was messier than that of PCB. The Darlington Array

ULN 2003 was used as a switch to turn the high-current LEDs on and off. Finally, the buggy of Group 4 successfully tracked the white line and completed the Heat Race thanks to continuously optimized software code, resistors used and the height of sensors, which was a 4 mm gap between the TCRT sensors and the ground.

2.4. Software

The team made a deliberate choice to develop a robust, reusable, and efficient software solution for the project. The primary objective of the software was to serve as a control system, utilizing the inputs from line sensors to regulate the motor speeds and enable the buggy to track a white line. To accomplish this functionality, several key algorithms were implemented, each serving a distinct purpose. The complete list of implemented algorithms includes:

1. Sensor Reading Algorithm: This algorithm reads sensor values at regular intervals and converts them into relative line positions, providing crucial data for line tracking.
2. Encoder Reading Algorithm: Responsible for reading encoder values, this algorithm accurately translates them into velocity values, enabling precise control over the motor speeds.
3. Speed Control and Direction Control Algorithms: Two separate control algorithms were developed to regulate the speed and direction of the buggy. These algorithms will be discussed in greater detail in the subsequent section.
4. Bluetooth Control Algorithm: To facilitate comprehensive testing and control, a Bluetooth control algorithm was incorporated. This feature allows the team to monitor and manipulate various values (mainly control system tuning) of interest and provides a means to control the buggy using Bluetooth commands exclusively.

Throughout the software development process, the team prioritized code readability, modifiability, and ease of debugging. Consequently, the aforementioned algorithms were implemented using three distinct classes: the Encoders class, the Sensors class, and the Motor Control class. By organizing the codebase into separate source files and employing related encapsulation principles, the team achieved improved code organization and maintainability. Additionally, the use of setter/getter functions within the classes enhanced data abstraction and ensured controlled access to class variables.

The Motor Control class, inheriting from the Encoders and Sensors classes, encompasses the control algorithm responsible for coordinating the buggy's movement. This inheritance hierarchy promotes code reuse and encapsulates the necessary functionalities within a single class.

To centralize common definitions and macros used throughout the code, a dedicated source file named ESP4DEFINITIONS was created. This file encompasses essential declarations, pin configurations, and variable initializations, enabling easy management and modification.

2.5. Control

The control of the buggy is divided into two parts: Speed control and direction control.

The speed control or PI control worked as such: The bigger the difference between the objective speed and the current speed, the faster rise of the speed of the buggy was. This control worked with a proportional constant with a value of 0.0005 and an integral constant with a value of 0.0001. This control directly altered the PWM output to the motors.

This control was tuned for the maximum speed of 1 m/s. With these constants, the oscillations of the speed are high with peak overshoot of 20% of the maximum speed. This means that the buggy required a smaller proportional constant but limited time and lack of infrastructure could not allow further testing. Thus, the speed control and its constants remained untouched throughout the heat. Regardless of such limitations, the control managed to perform well on slopes and throughout the heats.

The direction control or PD control aimed at controlling the speed of the wheels individually when the line was not detected by the middle two sensors. The middle two sensors had no influence on the PD control but rather worked as a switch: whenever they were not detecting the line, the PD control would operate and adjust the speed of the wheels as required and when they were detecting the line the PD control stopped working. As the line was detected by the sensors, other than the middle ones, the offset from the centre of the buggy would be recorded as an error and multiplied with the proportional constant and with the derivate constant after the error is derived. The result from the two would be added and used to determine the speed of the left wheel or right wheel: if the error is positive, then the turn is right and if the error is negative then the turn is left.

As the line detected by the sensors was further away from the centre of the buggy, the bigger was the value of the error. Thus, the angular speed of the buggy was increased.

Both control algorithms were implemented to be nested. The direction control algorithm’s output was fed to the speed controller input for each wheel. This allowed a successful performance of the TD3 and the TD4. One downside of the control is that tuning required extensive work and time thus limiting the full potential of the buggy.

3. Team Organisation and Planning

3.1. Project Objectives

The team’s initial objective was to improve and learn to work as a team, regardless of the project’s outcome. Every member gathered and explained their own capabilities which would prove beneficial to the team. This discussion allowed the team to plan a proper outline before presenting it on a Gantt chart. As the project progressed, the group scored well in each Technical Demonstration. It gradually became the group’s objective to motivate each other in order to achieve a respectable rank for the race.

To achieve the objective, the group aimed to gain detailed knowledge about motors and sensors through the project. The required gearbox ratio and several line sensors were tested in the lab. Based on the outcomes, Group 4 designed and built the buggy according to milestones set in the Gantt Chart which contained two Design Reports including Electric Motor Characterisation and Gear Ratios, and Technical and Sensor Characterisation, as well as three Technical Demonstrations that require the following deliverables respectively: motor control, sensors, control/steering. Successful completion of the fourth technical demonstration, the heat race, was the main aim of the project.

3.2. Gantt Chart

During the project duration which spanned 50 weeks, a Gantt chart was made to organise the whole teamwork distribution shown in Figure 4. Each team member was given a role, and each of them managed the role given to them expertly. However, the initial Gantt chart experienced changes throughout the entire year. The first semester of the academic year consisted of everyone carrying out lab experiments and calculations for the building blocks of the buggy. These deliverables did not require any utilisation of specialised skills during this period; hence each team member experienced an equal workload and similar tasks. Consequently, the deliverables of the Gantt chart did not change in resources, except for minor changes in delivery dates.

A different situation occurred during the second semester, where each team member was required to contribute to the group according to their own specialised skillset. The Gantt chart was made referring to the roles of each team member. In Proposal Report [2], Asim is the Secretary, Doruk is the Software Lead, Mur is the Mechanical Lead, Akmal is the Design Lead, and Zhixin is the Electronic Lead. During the writing of the Proposal Report, each team member was given their own section regardless of their roles. Then, Mur, Akmal and Zhixin all took part in the assembly of the buggy after the submission of the report. Asim and Doruk were tasked with encoder readings and the control of the motor using PWM. The encoders however had problems with terminal connections, causing the software development to be delayed. Since the delivery date of TD1 was not adjustable, overutilisation of resources occurred during this week.

The following three weeks pertained to TD2. The systems diagram and PCB submission were done ahead of the delivery date, but some errors in calculations and designs held back the group from going ahead with the sensor's assembly. The microcontroller coding then had to be shifted a few days late of the actual date, yet the group still managed to achieve the TD2 deliverable excellently.

It is shown on the Gantt chart that the TD3 demo should be completed by 18th April 2023, however, due to the Easter break, the deliverable was moved to 20th April 2023. The TD4 demo was also moved from 21st April 2023 to 2nd May 2023. This shift allowed the group to polish both the hardware and software more appropriately for the heats. Results and observations from the buggy should be discussed in the following sections.

During these extra few days, the group made significant changes to the buggy. From the Gantt chart, all team members needed to help with improving the code, but this was adequately done by three people. As the sensors needed to work in concert with the control algorithm, some of the team members went back to testing to improve the sensor readings. The initial sensor reading gave little disparity between the black and white line, causing the buggy to derive from the track randomly. Using the original resistor pair 55 Ohm and 10k Ohm, the buggy was following the line with vigorous oscillations. Changing the height of the buggy could solve this to a certain extent, but it will allow more ambient noise to interfere with the readings. The group then finalised a resistor pair of 120 Ohm and 4k7 Ohm, resulting in a much smoother line following algorithm. This resistor pair value gave a larger difference between the two contrasting colours, up to 4 V in magnitude. A wider PCB design was also suggested to enhance the range and turning capability of the buggy. However, this was not possible due to time constraints, as a new PCB could also mean a complete overhaul of the control algorithm.

As the buggy was limited by its hardware, the software was then focused on by the group. Initially, the group agreed to use PID (Proportional Integral Derivative) control as it was the best option to steer the buggy. The group failed to achieve this as the sensors were impeding the precision of the control algorithm. The best option was to implement the PD control, even though a large derivative constant K_d can cause the control system to oscillate more. Due to this being the limiting factor, the group concurred to let the buggy trudge the tracks slowly during the Technical Demonstration 4. This modification allowed the buggy to navigate through the corners as smoothly as possible, albeit very slowly. This manoeuvre allowed Group 4 to achieve full available marks as all requirements were carried out perfectly.

3.3. Teamwork

In hindsight, the group encountered many difficulties hindering the progress of the project. A decent rapport was established properly during the initial weeks, although the group still had a few miscommunications and gaps in their understanding. From Proposal Report [3], the group communicated through WhatsApp chat group, which was not the most effective platform to communicate. A lot of these were resolved through face-to-face meetings, both formal and informal. The group also struggled with meeting deadlines as consequences of hardware problems. All the team members gave their absolute best, and none of them procrastinated during this period albeit unforeseen circumstances. This collective perseverance allowed the team to support each other regardless of their own skill set. All the deliverables and deadlines were achieved above the expectations of the group, even though they were marginally close to the time limit.

The outcome of this project can be improved tremendously with sufficient pre-requisite knowledge of the hardware and components. The team realised that numerous mistakes were made during the designing process, and these errors were translated onto the buggy causing the previously mentioned hardware problems. Problems such as the resistor values causing a larger ambient noise could be prevented simply by doing more research and calculations. As the team members now also have a general idea of the marking criteria in the Technical Demonstrations, they can create a more vivid end goal for each deliverable and work together to achieve it. The overall teamwork of Group 4 will certainly be extremely excellent should the project be repeated.

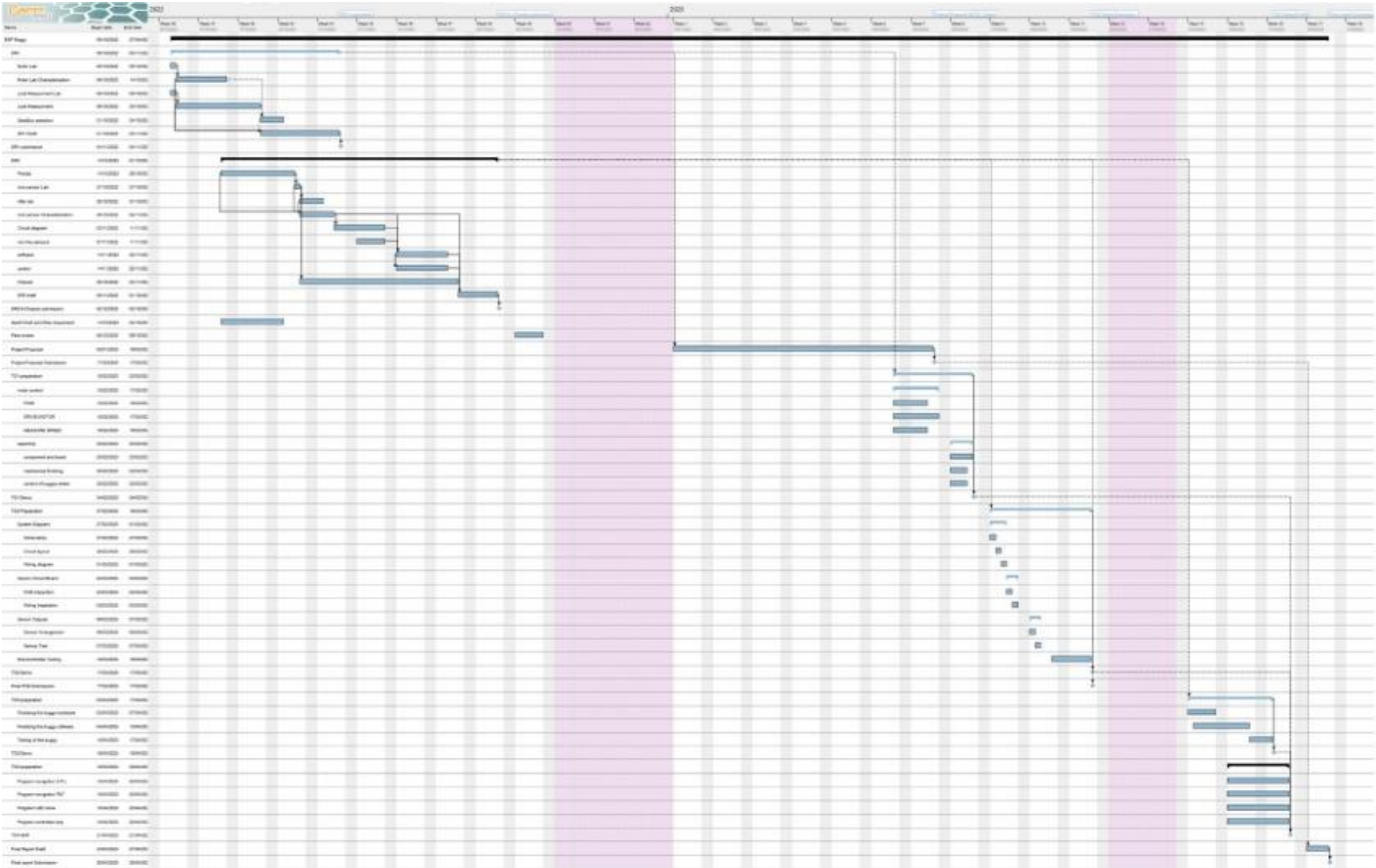

Figure 4 – Gantt Chart of Group 4

4. Budget vs Outturn

4.1. Replacement Costs

Table 3 – Cost of Replacement Component

Manufacturer Part	Qty	Seller	Seller Part	Cost Each
6 Way SIL Header	2	Farnell	2751384	£0.21
Total Cost of Replacement				£0.42
Remaining Contingency Budget Before Replacement				£23.48
Remaining Contingency Budget After Replacement				**£23.06**

The cost of components replaced during all Technical Demonstrations this semester is shown in Table 3, except for items that were given away for free, such as resistors and TCRT5000.

During the semester, a replacement of the original sensor printed circuit board (PCB) was necessary due to flaws that resulted from an accidental short circuit. Fortunately, the replacement of the PCB only required replacing two 6 SIL Way Headers, with a total cost of £0.42. This expense was covered by the remaining contingency budget of £23.48 [3]. It is worth noting that the replacement did not exceed the budget limit, and after the replacement, the contingency budget is still within the limit of £23.06.

4.2. Product Sales

Table 4 – Overall Cost of Buggy

Manufacturer Part	Qty	Seller	Seller Part	Cost Each
Resistor	12	-	Various	£0.10
ULN2003	1	RS	686-8209	£0.47
TCRT5000	6	RS	818-7524	£0.72
AEAT-601BF06	2	Farnell	2467469	£21.40
HM-10	1	RobotShop	RB-Suf-03	£13.53
Chassis	1	UoM	198.27 x 140.00 x 3.00 mm and 140.00 x 140.00 x 3.00 mm	£3.69
Front Wheel	1	Polulu	#955	£2.47
Rubber Tyre	2	Rapid	06-0654	£1.45
Motor A	2	RS	238-9737	£3.92
Gearbox Box	2	UoM	-	£7.00
NUCLEO-F401RE	1	Avnet	NUCLEO-F401RE	£15.00
MBED-016.1	1	Farnell	2468119	£42.54

STM Breakout	1	-	Proprietary	£10.00
I/O Board	1	-	Proprietary	£30.00
Controller Board	1	-	Proprietary	£30.00
Jumper Cables	1 bag	Farnell	2396416	£4.19
8 Pin IC Base	6	RS	1077344	£0.56
Sensor Mini PCBs	6	UoM	-	£1.00
4 Way SIL Header	2	RS	669-5314	£0.27
Battery Holder	1	Farnell	3829583	£2.28
Battery	8	Farnell	-	£2.00
Insulation Tape	1	RS	227-2976	£2.56
Stripboard	1	RS	286-5841	£4.16
6 Way SIL Header	2	Farnell	2751384	£0.21
Pan Head Screw	1 bag	Farnell	3666826	£2.35
Hex Female/Female Standoff	12	RS	222-395	£0.22
Velcro Straps	1	Farnell	2400992	£3.55
Overall Cost of Buggy				**£268.81**

The overall cost of the buggy is shown in Table 4 above. The procedure handbook has information on manufacturing parts and cost per part. The table is divided into two sections: freely provided (orange) and purchased (red).

Every business incurs expenses, including marketing and employee payroll that must be paid to sustain operations. During the development of a product, improvements can be made between the prototype and the final product. These improvements might include the use of new materials or the implementation of better technology. In the case of the buggy project, a new material for the chassis was considered, and the team switched to a lithium-ion battery as it lasts longer than the previous battery used.

One critical aspect of creating a successful product is protecting intellectual property. A patent may be required to protect a company's inventions and ideas from being stolen or copied by competitors. However, obtaining a patent can be costly, and the process can take a long time, which can be a significant burden for a business. Despite this, protecting intellectual property is vital for the long-term success and sustainability of a company.

To attain long-term success, profitability plays a crucial role, and a company ought to aim for a profit margin of no less than 25% to account for all business expenses. As indicated in Table 4, the total manufacturing cost for a buggy is roughly £268.81. However, a company could lower the cost to £230 per unit by using commercial production techniques for line-following buggies. By selling these buggies at a price of £290, the company could generate a profit margin for its operations.

5. Analysis of Heats

5.1. Preparation for Heats

After the team completed Technical Demonstration 3, preparations for the heats began. To guarantee peak performance, the team met in the lab at least three times a week to fine-tune the K_p and K_d values of the PD control system in use. Various values of K_p and K_d have been tested in order to achieve optimal tracking of the white line with the highest degree of smoothness possible. Furthermore, speed-sensing technology was used to keep the buggy moving at a constant speed throughout the entirety of the track.

To ensure that the buggy was fully operational during the Technical Demonstration days, the team arrived early and took necessary measures. The batteries were removed and recharged on the previous day to ensure that the batteries had enough power to operate the buggy and all of its sensors. This approach guaranteed that both the software and hardware components were fully functional and capable of performing as intended.

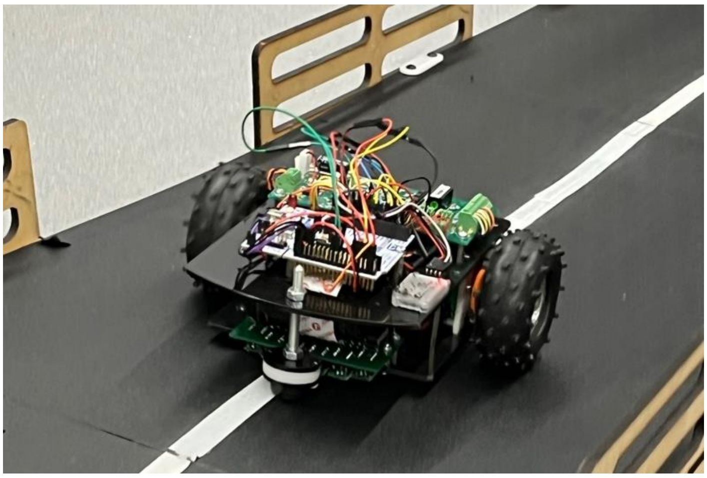

Figure 5 – Buggy During Testing

Figure 5 above shows a buggy that was being tested going uphill on a track in the Dry Lab before Technical Demonstration 4 took place.

5.2. Critical Analysis of Buggy Performance and Changes Between Heats

After successfully completing the first heat at a safe speed, the team increased the speed with a different proportional constant value. To test it, the team used a makeshift track and managed to get satisfactory results. Before the start of the second heat, one of the motors stopped working. Unfortunately, unaware of such a problem, the group tried to challenge the track a second and final time but failed immediately because the buggy derived from the track at the starting point. Nevertheless, the team managed to achieve full available marks, despite the slow speed.

5.3. Successful and Worst Features of Buggy

Successful features:

- The size of the buggy's chassis is ideal for manoeuvring turns on the track.
- The TCRT5000 sensor can distinguish between a white line and a black surface and can provide precise measurements through Bluetooth.
- The programming code enables the buggy to track the white line on a black surface.
- The buggy has a low centre of gravity because the weight is distributed evenly between the front and rear of the vehicle, and it is not too tall.
- Immaculate ESP4DEFINITIONS.h source file allows swift modifications of the buggy.
- Software has security functionality which limits the PWM thus avoiding extreme current to the motors.

Worst features:

- The placement of the battery on the lower part of the top chassis creates challenges when it comes to replacing or recharging the battery.
- Sensor's height from the surface is ~0.5 cm which requires calibration before each test otherwise the sensor readings are erroneous. Any surface bump could give false readings.
- Sensors falling out of their sockets.
- Middle sensors are not influencing the PD control but rather work as a switch for the PD control as they are always reading the line if the line is in the middle of the buggy.
- PI control of the speed control limited the overall speed of the buggy during line following.
- Front wheel and sensors in the middle are offset. The buggy is adjusting all the time for such reasons.

6. References

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