**Department of Electrical and Electronic Engineering**



Embedded Systems Project 2023-24

Final Report

Group Number: 43

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# Executive summary

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# Introduction

**Overview:**

This document outlines the comprehensive efforts undertaken by our project team over two semesters to design and manufacture an autonomous buggy capable of navigating a track by following a white line, while avoiding the track edges. This report highlights the integration of advanced technologies, control systems development, and effective project management.

A machine with a vehicle on top

Description automatically generated with medium confidence  
**2.1 Technology Integration and Innovation:**

Figure 1 - Photo of final buggy

The team strategically selected TCRT5000 sensors for their resistance to environmental disturbances, enabling precise line detection under varying lighting conditions. To complement this, careful consideration was given to the motor and gearbox configurations to address challenges like slopes and sharp turns. The chassis was constructed from Acetyl, chosen for its lightweight, cost-effectiveness, and strength, which adequately supports all mounted components and endures the demanding race conditions.

**2.2 Control System Development:**

A Proportional Derivative (PD) control algorithm was implemented to reduce track oscillations, enhancing the buggy's speed and navigation accuracy. This required the development of specialized software designed to run efficiently on the STM32F401RE microcontroller, ensuring system stability and responsiveness.

**2.3 Hardware and Software Coordination:**

The project's success was significantly attributed to the meticulous design of hardware circuits and sensor layouts, ensuring stable and accurate power and signal transmissions. This precision enabled seamless software integration, allowing sensor data to be effectively utilized for controlling actuators like motors.

**2.4 Impact on Planning and Organization / Gantt Chart Adjustments:**

Effective team collaboration and project management were essential. Responsibilities were clearly defined for each team member, which streamlined workflows and improved efficiency. A Gantt chart facilitated clear goal-setting for each phase and task prioritization. The project adhered to this schedule, maintaining consistent goals, staying within budget, and delivering high-quality results.

**2.5 Group Difficulties and Improvements:**

While there were no significant communication issues, there was a recognized need for enhancing technical skills. The team responded by increasing regular meetings and organizing technical study sessions. Should the project restart, an earlier in-depth study of the manual's content is planned to improve understanding and application of both software and hardware. Market-based adjustments

and enhanced team collaboration are also considered to refine the product's market readiness.

# Final System Components Summary

Each system component plays a significant role in ensuring the smooth navigation of the buggy along the white line and facilitating proper movement, including following flat tracks, making turns, ascending slopes, descending slopes, and controlling stops. Throughout the second semester, numerous adjustments have been made to various components, such as reconfiguring the sensor board arrangement, relocating battery holders and so on. These changes are discussed in greater detail in the following sections.

**3.1 Mechanical components**

The mechanical components are the most basis part of the entire system. This part includes gearbox selection whichis connected between motor and wheels to increase the speed of wheels, the chassis which support all the electric components and make the buggy goes into a properly balance to follow the white line.

**3.1.1 Gearbox selection**

Table 1 – Table showing gearbox selection characteristics [1]

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Pinion Gear** | **Intermediate Gear** | **Gear on the final drive** | **Required scaled torque** | **Required Torque with inefficiencies** |
| 16 tooth | 50/10 press fit gears (orange) | 48 tooth | 0.0066 | 0.0092 |

In the motor characterisations section, the measured KT value ≅ 0.07. Additionally, the torque output is 0.00888 and 0.00962 for 1.2 A and 1.3 A respectively by using the equation (1) [2].

(1)

where T is torque, KT is torque constant, I is the current and TLoss is torque loss, and it is negligible.

Through the toque required and supplied toque, gearbox shows in the table is the most appropriate choice to achieve the required torque while not compromising on rotational speed.

**3.1.2 Chassis design**

In the chassis design, additional holes were added to ensure the stability and solidity of the buggy, especially for supporting the electrical components. Two holes, each with a diameter of 3 mm, were added to the top chassis and highlighted by green circles in Figure 1. These holes served to secure the Nucleo board and microcontroller using standoffs. Furthermore, a second set of four holes, aligned with the bottom four holes, were added into the top chassis. These holes, highlighted by red circles with a diameter of 3 mm in Figure 1, stabilized the entire buggy using standoffs. Additionally, another four holes on the top chassis were introduced, highlighted as blue circles in Figure 1. These holes accommodated zip ties to stabilize the battery.

Additionally, an essential aspect of the design is the flexibility in positioning the battery. Originally, the battery was located between the two chassis of the buggy, secured in place with adjustable zip ties which is shown in Figure 2. However, during hill climbs, it was observed that the front end of the buggy would tilt upward. To address this issue, the decision was made to attach the battery to the front wheel of the buggy, thereby increasing the weight at the front end and 电脑萤幕

低可信度描述已自动生成improving stability. Shifts the centre of the mass forward, away from the wheel, which is shown in the Figure 3. The ability to freely position the battery is a crucial design consideration that contributes significantly to the buggy's performance and adaptability.

Figure 2 - Changes of holes in top and bottom chassis

图片包含 户外, 小, 卡车, 桌子

描述已自动生成A computerized machine with wheels

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Figure 4 - revised placement of battery

Figure 3 – Original placement of battery

**3.2 Electronic components**

The electronic components are also the significant part for the system, which includes the motors, motor drive board, microcontroller, and sensor board. These connected components will help the buggy recognize the white line and follow it as well as do the turnings. Furthermore, the Figure 4 is wiring diagram [3], which shows how these electronic components were connected.

图示, 示意图

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Figure 4 –Wiring diagram

**3.2.1 Motor drive board**

Motor drive board plays a crucial role in controlling the buggy, it is the middle part which connects microcontroller and motors. It can control the buggy’s speed and turnings depending on the signals that received from the PCB circuit board. There are two methods to control wheel speed, they are unipolar and bipolar. In our team, bipolar is selected, which is about when the encoder output value over 0.5, the wheels go forward and the wheel speed increases as the output value increases. Conversely, when the encoder output value below 0.5, the wheels go backward, and the wheel speed decreases as the output value decreases [4]. Figure 5 shows the code of setting bipolar.

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Figure 5 – The code of setting bipolar

**3.2.2 Motors**

The motors provide the necessary propulsion for the buggy's movement. Each motor module has positive and negative terminals, which connect to corresponding ports on the motor drive board for power supply. In the wiring diagram, the connections for the right and left motors are designated as JP8\_1 and JP8\_2, and JP8\_3 and JP8\_4, respectively. Furthermore, a critical component of the motor modules is the quadrature encoder, which comprises two channels: CHA and CHB. For the left motor, the encoder is connected to pins PA\_15 and PB\_7, while for the right motor, it is connected to pins PB\_13 and PB\_14.

Additionally, equation (2) calculates the wheel speed, considering factors such as the wheel radius, encoder tick rate, gear ratio [5]. This equation enables precise control over the buggy's motion, allowing for accurate navigation and speed regulation.

(2)

**3.2.3 Microcontroller**

The primary function of the microcontroller is to interface with the PCB board, facilitating the provision of emitter power and the reception of detector output. This detector output enables the buggy to categorize into various states such as go straight, turn left and turn right. Furthermore, it interfaces with the motor drive board, connecting to bipolar 1 and 2, PWM 1 and 2, as well as the enable pins, which are essential pins for moving of the buggy.

**3.2.4 PCB circuit diagram and sensor board**  
The design of the sensor board underwent a change, resulting in the removal of one sensor initially intended to be positioned above the board. Originally, this upper sensor was meant to test ambient light, aiding the buggy in better distinguishing the position of the white line. However, it was found redundant. When placed below the bottom chassis, the sensors are unaffected by ambient light. This adjustment optimized the sensor board layout for efficient line-following functionality and the improved PCB circuit diagram is shown in the Figure 6.

**图形用户界面, 应用程序

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Figure 6 – Changed PCB diagram

**3.3 Control**

**3.3.1 Line Following and Buggy Control**

On the sensor board, there are five sensors placed at the bottom of the board, two sensors on each side of the board. The voltage difference between the left and right sides determines the rotation direction of the buggy.

**3.3.2 PID Controllers**

The control targets in the system are the angular wheel velocity, calculated from the analogue outputs of the gearbox encoders, and the line alignment of the buggy, which is calculated from the sensor output signal.

For these situations, the PID algorithm is the best, because the PID controller can control the movement of the buggy precisely, adaptably and smoothly, and it is well-suited for tasks such as line following in dynamic environments since it adjusts the control output based on real-time feedback from line sensors. The following equation (3) shows the calculation of PID controller [6].

(3)

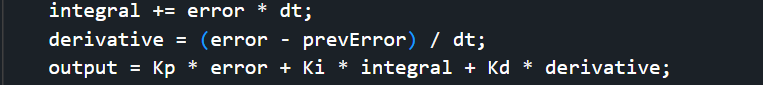
In the PID controller, each of P, I and D constants has different functions for help the buggy go through the white line. P can adjust the motor speed based on the difference between the desire position and the actual position. This term controls the buggy’s steering response and ensures that the buggy follows the white line. I can eliminate steady-state errors which can help the turning of the buggy go smoothly. D can eliminate the overshoot which means the buggy will not swing significantly and reduce the oscillations, allowing the buggy moves in a straight line. The Figure 7 shows the code of calculation of PID controller with errors which are the outputs when the buggy in different positions.

Figure 7 – the calculation of PID controllers

**3.3.3 Sensor outputs**

Illustrated in Figure 8, the buggy utilizes the output values from its 5 sensors to determine appropriate left or right turns. (Sensorcalc() return the value of sensor as 0 or 1.) Additionally, the microcontroller serves the purpose of judging potential issues within the buggy by displaying numerical output on the screen. For instance, if the buggy encounters difficulty ascending a slope due to the speed, the screen can display the current speed, aiding in identifying state changes during slope traversal. This functionality helps a lot when testing the code.

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Figure 8 – The categorized states depend on the outputs of sensor

**3.4 Software**

**3.4.1 Functional Summary**

The buggy must follow a white line autonomously on an unfamiliar track, avoiding deviation or falling. Additionally, it should respond to a Bluetooth signal, allowing it to turn around and follow the white line back when necessary.

**3.4.2 The process of working steps in the buggy**

The positioning of the buggy involves phototransistors gaining information from LEDs, with the microcontroller comparing voltages from each phototransistor to calculate the buggy's position. A Proportional Integral Differential (PID) loop is employed to ensure the buggy does not deviate from the line, by regulating the data received from the phototransistors. The voltage supplied to the motors is then derived based on this positional data with the velocity of the wheels determined by the encoders on the wheel shaft, and the microcontroller calculates to determine the wheel velocity and stores this data. The current motor power is generated based on the PID loop, and the microcontroller needs to know the current and voltage being supplied to the motors before changing them. The motors receive specific voltage/current, converted to PWM in the microcontroller, and then transmitted to the motors. Buggy rotation is achieved through a Bluetooth signal, interrupting the program to execute the desired action, such as spinning the buggy around 180⁰ [7].

**3.4.3 Discussion on speed control**

Initially, for speed control, the track was categorized into flat, uphill, and downhill sections, as illustrated in Figure 9. In flat track, lower speeds were preferred to ensure precise cornering, as lower speeds facilitated clearer extraction of white line information by the sensors. Conversely, on uphill sections, the buggy needed to increase its speed, as the original speed on flat terrain might not be sufficient for a successful ascent. Vice versa for downhill sections. However, the code does not work properly. For instance, the buggy experienced delays in accelerating uphill and decelerating downhill. To address this issue and enable faster responses, the code was updated. The revised code simplified the approach by focusing on accelerating when the speed was insufficient and decelerating when the speed was excessive, without differentiating between track sections. Figure 10 illustrates the logic of the updated code.

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Figure 9 – The old code for speed control

**屏幕上有字

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Figure 10 – The old code for speed control

**3.5 Conclusion for the parts work well and energy monitoring**

The design of the buggy's chassis is great, which is allowing for flexible battery placement to adjust the centre of gravity. This prevents tilting when going up the slope. Additionally, the square shape of the chassis enables smooth 360° rotations without any issues related to the buggy's dimensions. The sensor board design is also great. Placing the middle sensor slightly forward enables better handling of line breaks. Moreover, positioning the sensor board at the bottom chassis of the buggy ensures minimal interference from ambient light, enhancing sensitivity in detecting the white line's position. For instance, voltage outputs of 0.7V and 1V signify the sensor's placement on the edge and centre of the white line, respectively, while 0V indicates other scenarios.

In terms of energy monitoring, we didn't incorporate additional sensors dedicated to this purpose. However, we developed code to test the battery voltage and current, aiming to ensure smooth and stable battery performance. Typically, Li-ion batteries exhibit consistent discharge voltage from around 80% to 20% state of charge [8]. Figure 11 illustrates the code used for testing the voltage and current levels of the remaining battery.

# Team Organisation and Planning

The main objective of the project was to produce an autonomous line-following buggy capable of completing an unknown track within the academic year, throughout the development, manufacturing and testing of the buggy this was always the focal point of each decision which allowed our group to achieve this main objective.

This objective alone however, wasn’t enough to guide the entire process of making the buggy as there were specifics that the end product needed to adhere to in order to meet the requirements, these included: size limitations on the buggy due to track size and the need to make a 180o turn; the ability to go up a 18o slope; be able to receive and react to Bluetooth signal; handle 6 mm breaks in the line and be able to stop within 20 cm from the end of the line. These other requirements meant that focus was shifted between different aspects of the buggy depending on what was going well and what needed fixing. This was further amplified by the technical demonstrations taking place throughout the year which put emphasis on varying aspects of the buggy, an example of this being the first major test of the buggy, technical demonstration A, focusing on motor functionality independent of the sensors.

With all of this the project saw many changes in how the final product came together through the testing of the buggy, the timings and organisation of the group and most critically the goals and objectives set internally by the group that effected the progress of the project. The Gantt chart was a key aspect in the organization of the project as it set the timeframe for the milestones needed to complete the buggy within the specified timeframe, this was made early in semester 1 and as such estimations needed to be made which were subject to change. One instance of this was when deciding which method to use for the speed control for the motors, the code was previously running off of a state switching system that was unreliable, to solve this the group attempted two different solutions, one based off of the existing code and the other based on a new control method. This split in the group was not planned and caused some complications with the development of the buggy as other functions were put off to the side during the time spent fixing this issue. Despite this, the situation seemed to be delt with effectively and arguably time was saved in solving this specific problem as the two teams within the group working in parallel meant more individual effort was inputted and therefore the solution was reached quicker.

**4.1 Reflection on plan and deliverables**

Throughout the project, early deadlines were set for drafts of each deliverable to ensure that each one was completed on time. This allowed for more time to develop and improve things such as code and reports, as well as planning for possible delays caused by other deadlines or unpredictable events such as illness.

So far in the project everything has gone to plan, with the key exceptions of TDC. Both DR1 and DR2 were completed on time with previous drafts being checked and improved upon, which gave marks respectively of 68% and 70%. As these were the first reports of the year, these were good development opportunities for the whole group in report writing. This is reflected with the proposal report mark of 78% which shows an upward trend in the marks achieved throughout the year.

Whilst TDA & TDB went to plan, with respective marks of 95% and 91%, and minimal marks dropped due to imperfections in cable management and code logic errors, TDC yielded a mark of 60/80, not considering additional marks for top 4 speeds in heats, hardware errors limited the functionality of the code. This also meant that the speed of the buggy was difficult to optimise for this technical demonstration.

Despite the non ideal performance within the last assessment criteria, the overall deliverables of the project were met. This included designing a automated line following robot buggy that is capable of following a white line on a contrasting matte black track. This was tested at multiple points during development, with motor control and sensor development being tested during TDA, line sensing and the control algorithm were tested during TDB and complete functionality in TDC.

The buggy is capable of a controlled stop at end sections of track, whilst also being able to initiate a 180 degree turn via Bluetooth intervention at any point during run time.

**4.2 Group conflict and resolution**

Throughout the year long project, there has been minimal friction with the group. With disagreements on how to approach a task being resolved either with a vote or having multiple teams rigorously test these ideas. The most prominent issue during this project has been scheduling. This is due to the members of the team being split across 3 overlapping degree streams, which means that different group members have varying workload and availability. This has been overcome throughout the accessibility of online meetings, as well as scheduling group work after reoccurring shared activities.

**Reflections on teamwork**

If the project was to be attempted again, the teamwork could be improved by more team building or recreational activities. The other aspect where the teamwork could have been improved would have been more concurrent streams of development by splitting the group up into sub groups to have more code parameter testing occurring at the same time.

# Budget vs. Outturn

In a project, budget is an integral part. It is inseparable from the formulation, actual execution, and final results of the entire plan. The first main function of Budget is to allocate resources. This resource includes funds, human resources, basic materials, etc. invested in each stage of the project. The second function is that budget can determine the general goal and scope of the project, ensuring that project personnel have consistent work goals to improve efficiency. Budget also plays a big role in helping the project team conduct risk management, which should include preparation for unexpected events.

**4.1** **Replacement costs and earlier prototypes**

During this project, most basic materials and components were provided free of charge by the college, but many additional or spare parts also had to be purchased. In the last calculation, the basic parts of this buggy cost about 298 pounds. The college has prepared a reserve fund of 40 pounds for us, which is about 13% of the cost of the buggy. We used the spare money to buy some extra batteries, sensors, tape, etc.

Table 2- replacement cost

|  |  |  |  |
| --- | --- | --- | --- |
| Components | Quantity | Unit Price | Total Price |
| batteries | 8 | 3.25 | 26 |
| Back-up sensors | 10 | 0.72 | 7.2 |
| tapes | 1 | 1.5 | 1.5 |
| total |  |  | 34.7 |

The reason why we bought some spare batteries during this project is because during the measurement process, we found that under different battery voltages, the buggy would run at different speeds and uphill states. But since we are using rechargeable batteries and the charging time is a bit long, we must buy some additional batteries to keep the buggy running continuously and in good operating condition.

The sensors are soldered on the front PCB board of the buggy, and to ensure the highest working efficiency of the sensors, these sensors are only a small distance from the ground. Therefore, during the entire test process, it is easy for the sensors to be damaged due to impact. We had to prepare more sensors and solder them to deal with emergencies.

**4.2 Labor costs and site fees**

Salary we set for meeting and review: Each member is paid £12 per hour.

Salary we set for the lab and the design report: Each member is paid £15 per hour.

Cost we need to rent the meeting room: It costs £10 per hour.

Cost we need to rent the dry lab: It costs £50 per hour.

Table 3 – labour cost

|  |  |  |
| --- | --- | --- |
| Types | Total time (h) | Total cost (£) |
| Pre-lab | **96** | **1440** |
| Lab | **96** | **1440** |
| Report | **185** | **2775** |
| Meeting | **184** | **2208** |
| Meeting room | **184** | **1840** |
| Dry lab | **23** | **1150** |

The total labor costs and site fees are around £10853.

**4.3 The price that might sell the buggy.**

When we price a product, we need to consider many factors, including cost, market demand, competition from similar products, taxes, and profit margins.

The costs include direct costs, indirect costs, R&D costs, and marketing costs. In this project, we calculated these costs into the construction cost of the buggy itself and the labor cost.

Table 4 – total cost

|  |  |  |  |
| --- | --- | --- | --- |
| Buggy costs (£) | Back-up fees (£) | Labor costs (£) | Total costs (£) |
| 298 | **40** | **10853** | **11191** |

According to our market research, there are many buggies of the same type as ours, and our core competitiveness can only be higher quality, technology, and better raw materials. Therefore, the market demand for our buggy is not very high and we cannot have a high price. During the research, we found that this type of buggies is generally priced around 50 pounds. We estimate the production volume to be about 1,000 units, because too low sales volume cannot make up for our labor costs.

In this project, we need to consider about the 20% tax in the UK. Usually in the UK, we need to consider a VAT of about 20%, so we need to add 20% to the final cost of our buggy. As for the profit part, we know that the general profit margin in the manufacturing industry is around 10% to 20%, depending on the complexity of the product and the difficulty of manufacturing. Since the design and manufacturing of this buggy are not particularly difficult, we decided on a 10% product profit margin.

When this buggy enters mass production, I believe we can reduce the manufacturing cost of each buggy itself to about 100 pounds. Taking into account the labor cost of about 12 pounds allocated to each buggy, plus a profit margin of about 10%, we decided that the final retail price of the buggy would be about 138 pounds.

# Analysis of Heats

**6.1 Heat preparation:**

Preparation for the heats involved multiple things such as PID tuning at higher speeds for better times, replacing multi core power connections for more robust single core wires, as the multi core wires had unreliable connections.

anticipated issues with the track on heat day, differing reflectivity of the line and varying ambient light conditions which was combatted by testing the sensors on different surfaces and in different ambient lighting conditions. Issues with battery voltage, solved with pretested batteries.

the strategy for the heats involved using two separate programs, the first program with a slower speed to fulfil the assessment criteria, the second program had a faster speed to achieve a more competitive time. This approach allowed an attempt at a high speed without compromising completion of marking criteria.

**6.2 Evidence of testing**

A robot on a track

Description automatically generated

Figure 11 - evidence of buggy testing

**6.3 Critical analysis and summary of heat performance.**

Heat 1 & 2

Both in heat 1 and 2 the buggy had similar behaviour where the buggy managed to get to the top of the ramp and execute the Bluetooth interrupt, but the buggy fell short where on the way down the buggy did not appear to dynamically control it’s speed and follow the line. This behaviour appeared to be due to the functions responsible for linear and angular speed control, which were attached to tickers, to stop functioning and updating the buggies speed. This appears to be a hardware issue, after investigating the code between heats.

Heat 3

During heat 3 we had the same issue of the speed control functions not working. However this time the speed control stopped working before the first time, which demonstrates that this error is not due to the Bluetooth interrupt. This final attempt was not continued as it was impossible to get higher marks than both heat 1 & 2.

In summation the buggy performed well apart from the possible hardware error which could have been solved by swapping out the microcontroller and rewiring the buggy. This fatal error meant that the buggy was not able to complete the track in any of the heats and qualify for the final heats.

# References

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