The University of Manchester

Department of Electrical and Electronic Engineering

Embedded Systems Project 2022-23

Final Report

Group Number: 5

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1. Introduction

The Embedded Systems Project included designing and developing a white-line following buggy based on a 32-bit microcontroller. The project involved sequential testing and development stages, with results summarised within design reports.

This document summarises the complete development of the buggy and evaluates the performance of the group at different stages. The project was divided into two sections primarily, the first part comprised laboratories and the theoretical development of the fundamental concepts including the estimation of coefficients of friction on the given track, speed required by the buggy to go uphill, motors that can be implemented to achieve the required standards and sensors that can be implemented accordingly. It also included developing a CAD design for the layout of the chassis, although this was modified before technical demonstration 3 to improve on a few design faults. The second section included the practical aspects of the project. This is when all the theoretical calculations were put together to the final development stages. A sensor board layout was developed at this stage and a wiring diagram was eventually to define the connections between the motor driver board, the microcontroller, the motors, and the batteries among other components like the switch.

The group also completed a set of deliverables including two design reports focusing on Motor Characterisation and Sensors respectively; a proposal document summarising the plan for the development of the buggy and the algorithm to be implemented and four technical demonstrations focusing on the motors, sensors, the performance of the buggy along sections of the track under given conditions and final heats where the buggy had to complete a given track independently. The buggy performed sufficiently in the first two demonstrations. The buggy didn't perform to plan in the third technical demonstration due to some faults with the connections on the PCB for the sensor board. It performed satisfactorily in the fourth technical demonstration.

The following are the images of the final layout of the buggy (after rebuilding the chassis): -

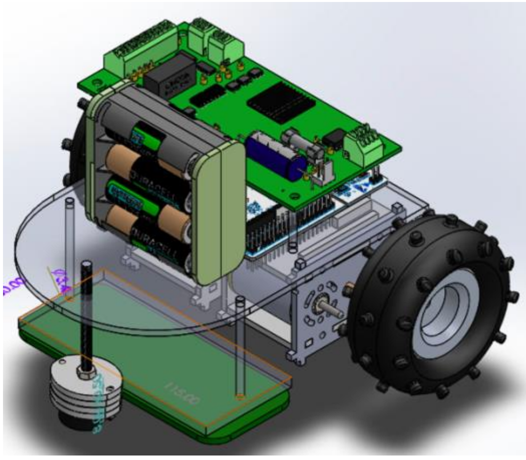

Figure 1: Buggy layout in Solidworks

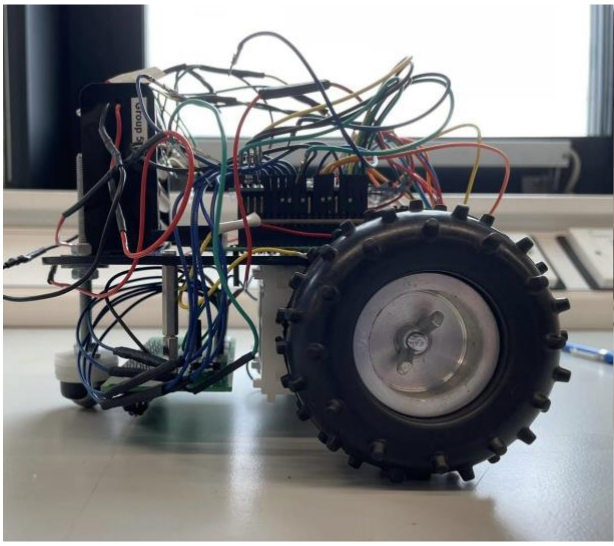

Figure 2: Side view of the buggy

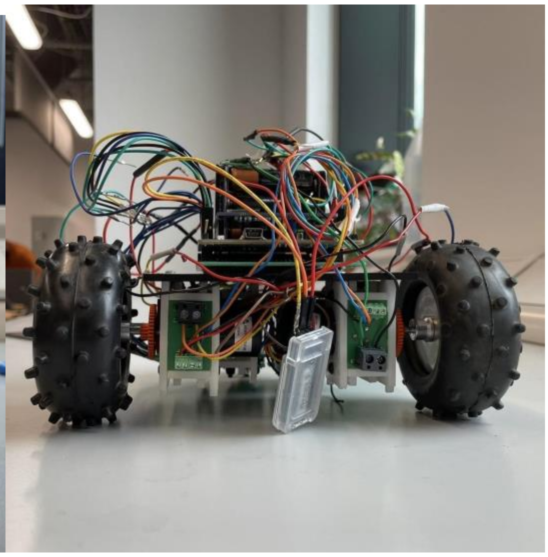

Figure 3: Rear view of the buggy

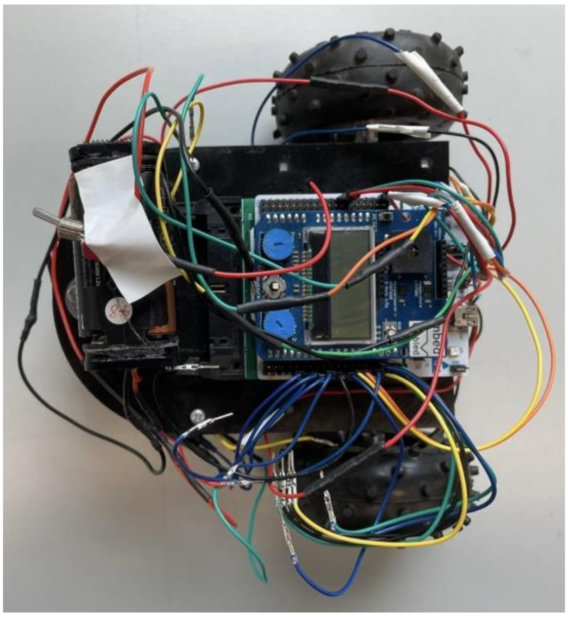

Figure 4: Top view of the buggy

2. Final System Components Summary

The Buggy needed to achieve the following tasks:

- Complete a left-hand turn followed by a right-hand turn.
- Ascend an incline.
- Turn around at the top of the ramp using a single Bluetooth command.
- Go back down the slope and navigate to the beginning of the track.
- Come to a controlled stop after the white line ends.

2.1 Buggy Construction

Now examining different sections of the design in detail, firstly the mechanical aspects are considered. According to the given information, the buggy was required to go up a slope which requires speed adjustment and hence the calculation of the required torque. After calculating the minimum torque needed to ascend the slope and comparing it to the maximum torque the motors could produce, it was decided that gearbox 2 was the best choice with an ideal torque ratio of 15:1 [3]. The gearbox allowed the buggy to travel up the ramp at a constant speed and allowed for variations in the speed by changing the input voltage to the motors. When designing the chassis, power efficiency and location of components were the main considerations. The buggy needed to be lightweight, therefore acetal was chosen. Additionally, the batteries were placed towards the front of the buggy to ensure the buggy has a smooth movement along the slope and don't fall backwards. This design was modified during the course of the project to correct a few design errors. The first design of the chassis didn't leave enough room for the PCB to be attached. This meant that the group had to send another chassis design and wait for it to be printed. This caused some delays in production and meant that the buggy wasn't ready to perform at TD3. The buggy's chassis was redesigned to make the buggy smaller and for better positioning of the PCB. The motor drive board was placed on top of the microcontroller for an ergonomic design. Although this made wiring tricky as the motor drive board needed to be unscrewed to access the microcontroller. The new design enabled the sensors to be closer to the track. The benefits of this were twofold. One it enabled more accurate readings and two it reduced the effect of ambient light. The sensor board was placed behind the front ball castor, so it doesn't collide with the ramp.

2.2 Electronics design

The sensor board was designed so that the sensor transistors could be read digitally. The digital route was chosen to improve sampling time. The sensors were switched on and off periodically using a ULN2003N Darlington array, to save power. All the sensors were connected to a single output of the Darlington array, as individual control of the sensors was not required. The five sensors chosen were TCRT5000 as characterised by [4]. TCRT5000 provides an inbuilt ambient light filter and is pre-packaged, this makes them robust and easy to implement. The sensor board also provided an extension header for the 5V supply from the motor board. The headers made the wiring more robust. Having a PCB improves reliability compared to a stripboard.

2.3 Control Algorithm

After analysing different options available, PID Controller was implemented to create an efficient line-following buggy. Initially, the buggy was tested with a PD (proportional derivative) controller, the idea being that this would improve the sampling time. But the sampling time gained didn't compensate for the control lost by not having integral action. The PID controller allowed the buggy to follow the line with minimal oscillations. Lower oscillations allow smoother runs and better lap times. The sensor test point is at 5V or Digital High when on the black region and goes down to zero when on the line. Hence the sensor inputs were first inverted and then used to calculate the error. The error was calculated using a sequence of if-else statements. The highest error value of 4 was attributed to the case when only the last sensor was on the line. In the ideal case when the buggy was centred on the line the error value is zero. This error value was then fed into the PID function which returned the PID value. The error value was multiplied with a proportional coefficient to get the P. The current error was subtracted from the previous error and multiplied by the differential coefficient. The error was multiplied by the integral coefficient and added to the sum of all integral values calculated so far. Lastly, all these values were added together to get the PID value. It was realised that the error value was calculated at a fixed time interval, hence this wasn't calculated and was directly incorporated in the PID coefficients. This eliminated the need for a separate timer to calculate PID values.

The speed control also used a PID controller. It was tuned to keep the buggy at a constant speed. This meant that the buggy would automatically increase the motor voltage when going up the ramp. The speed encoders on each motor allowed for speed calculation. The QEI library was used to read the encoders. The library allows easy calculation of the encoder tick rate from which a simple formula as stated in [3] is used to get the speed. The error value was then calculated as the difference between the reference speed and the current speed. The PID controller worked in a similar way to the positional controller. The turnaround was implemented using the HM-10 BLE module. The stop and turnaround were implemented using an Interrupt service routine. Any 8-bit unsigned int value sent to the Bluetooth module would trigger the interrupt. The buggy would then stop and turn around. To perform a U-turn the two wheels were spun in opposite directions for 0.6 seconds. This time was determined through trial and error. The code was written in a modular way for ease of collaboration and debugging. Separate

3. Team Organisation and Planning [2]

This section looks at the organisation and planning of the project. It discusses how the project was planned and charted through objectives and deliverables which all contribute to the achievement of the final project. A Gantt chart was used to keep track of objectives and deliverables as well as assign team members to deliverables. A shared google drive was used by the team members to share documents. The communication among the team members took place within a group on the WhatsApp Messenger platform.

The main objective of the project is to build an autonomous buggy designed to complete a track by detecting and following a white line on a black surface around corners, up and down hills. To achieve this goal, the main aim was simplified into smaller objectives with checkpoints where deliverables would be assessed. The checkpoints where the deliverables would be assessed are known as Technical Demonstrations. There would be four of these over the course of the second semester and upon the fourth technical demonstration, the project would have been completed.

The objectives for the first technical demonstration consisted of assembling(wiring) the buggy and successfully controlling the motors using the motor drive board and microcontroller. The assembly was completed within the provided lab times and the motor control software was worked on outside the lab but tested during labs. The workload was split evenly with two members focused on the motor software with everyone else assembling and wiring the buggy. All deliverables were completed on time which led to a successful first demonstration. This led to the group achieving a score of 100% by meeting all objectives.

For the second technical demonstration, the main objective was to program the sensors to be able to detect the line and display which sensor detects it on the display. This consisted of designing a schematic, circuit and wiring diagrams, building, and welding sensors onto a stripboard and programming it through a microcontroller. Another objective was sending a signal to the microcontroller from a smartphone through a Bluetooth module. These tasks were delegated during the weekly meeting by the group members. All deliverables were achieved in time for the demonstration.

The third demonstration was to show the ability of the buggy to steer itself left, right and to follow the line. Unfortunately, these tasks could not be completed due to an error in the printed PCB sensor board. The sensor stripboard which had previously been tested could not be used as it had been disassembled to assemble the PCB sensor board. There was too little time to correct this mistake as the group had assumed the PCB sensor board would be functional. This led to the tasks not being completed and the group getting a low score.

The problems from the third demonstration were revised and a new sensor board was printed, this allowed the group to begin testing and tuning of the PID control algorithm. Some group members were also focused on a redesign of the chassis to allow the various components to be assembled efficiently onto the chassis and give proper weight distribution to move up the slope.

The fourth technical demonstration was the amalgamation of all the tasks so far to complete the overall objective of having the buggy complete the track, which includes following straight lines, left turn, right turn, moving up the ramp, turning around with a Bluetooth signal, moving down the slope and coming to a controlled stop. A few moments before the final demonstrations, the buggy started behaving unpredictably, this was fixed by replacing the batteries on the buggy. The result was a successful completion of the track with the exception of the turnaround and complete stop.

In summary, breaking down the project into smaller objectives enabled the tasks to be delegated accordingly to each team member. This increased the overall productivity of the group and made sure that everyone contributed to the development. The progress of the project was assessed on a weekly basis through team meetings which included updates from each member on the status of their deliverable. The team members primarily communicated using WhatsApp as a platform and kept the group's google drive updated by uploading their end of deliverables regularly. The team also prepared a weekly journal outlining the individual contribution of each member and used it to communicate as well as keep their supervisor updated. The changes in the Gantt chart or the internal deadlines including reporting any difficulties faced during the project were communicated effectively among the members and sorted thereafter collectively and updated in the weekly journals. The objectives remained largely the same from semester 1 to semester 2. Although there was an addition of two new deliverables in semester 2 with regards to the redesign of the sensor board (due to faults in wiring) and buggy chassis to arrange the components more efficiently onto the buggy without obstructing the detection of the line by the sensor board. These objectives are grouped into presenting the practical aspects through technical demonstrations during different stages of development assessing different sections and functions of the design and writing reports explaining the procedure adopted and the reasons for it. The technical demonstrations were the deadlines for the deliverables. The deliverables were all achieved, however, there was a delay with the third technical demonstration due to a fault in the initial sensor board design as it lacked a few connections which were eventually redesigned but the time constraints resulted in receiving the sensor board after the TD-3 and hence resulting in penalties. The technical reports included four reports primarily including this final one. The first two focused on the laboratory results obtained for the motors and sensors which were required for the design according to given conditions and were fundamental in the development. The third one was a proposal document that was prepared at the beginning of the second semester which summarised all the design requirements and algorithms that were planned to be implemented and the proposed hardware design, although this was modified eventually for above stated reasons.

These complications required the team to adjust the Gantt chart and shift deadlines for the objectives from time to time. Mostly the team managed to keep up with the internal deadlines and checkpoints throughout semesters one and two. There were a few minor changes but the major one was the delay in sensor board preparation before the third technical demonstration, but it was later mitigated and everything was thereafter assembled, and the buggy was functional before TD 4. We also changed the allocation of responsibilities across the project as the team members handling the hardware were not having much stuff during the second semester, so they switched to managing the wiring and creating the wiring diagrams and soldering of components for the sensor board.

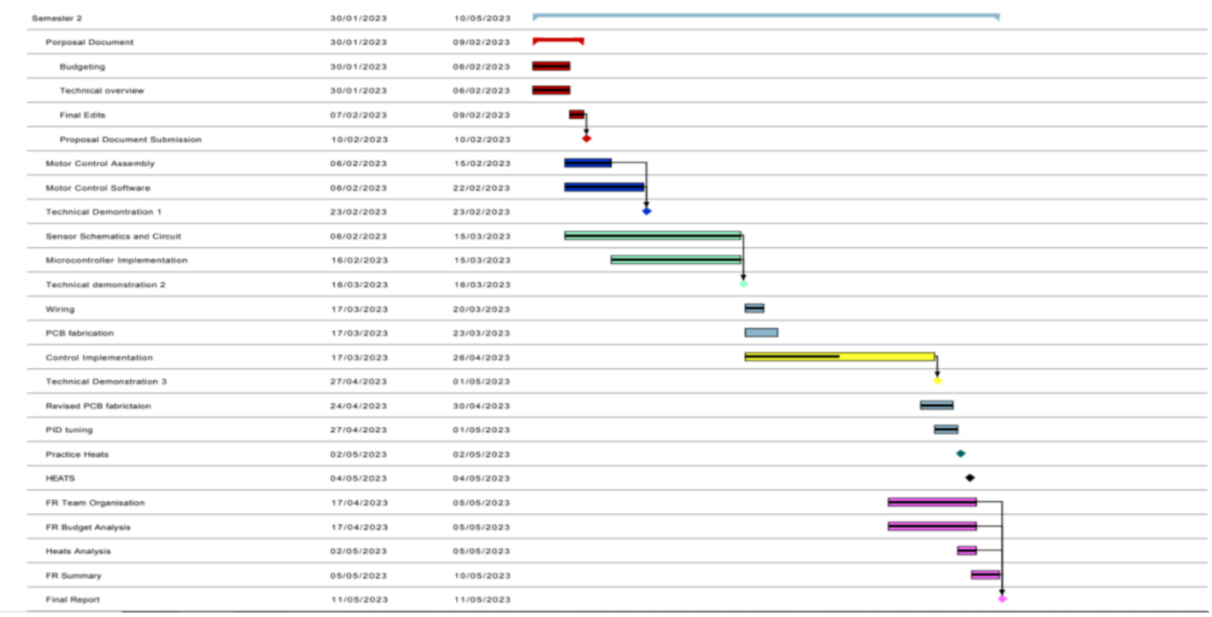

Figure 5: Revised Gantt chart for the second semester

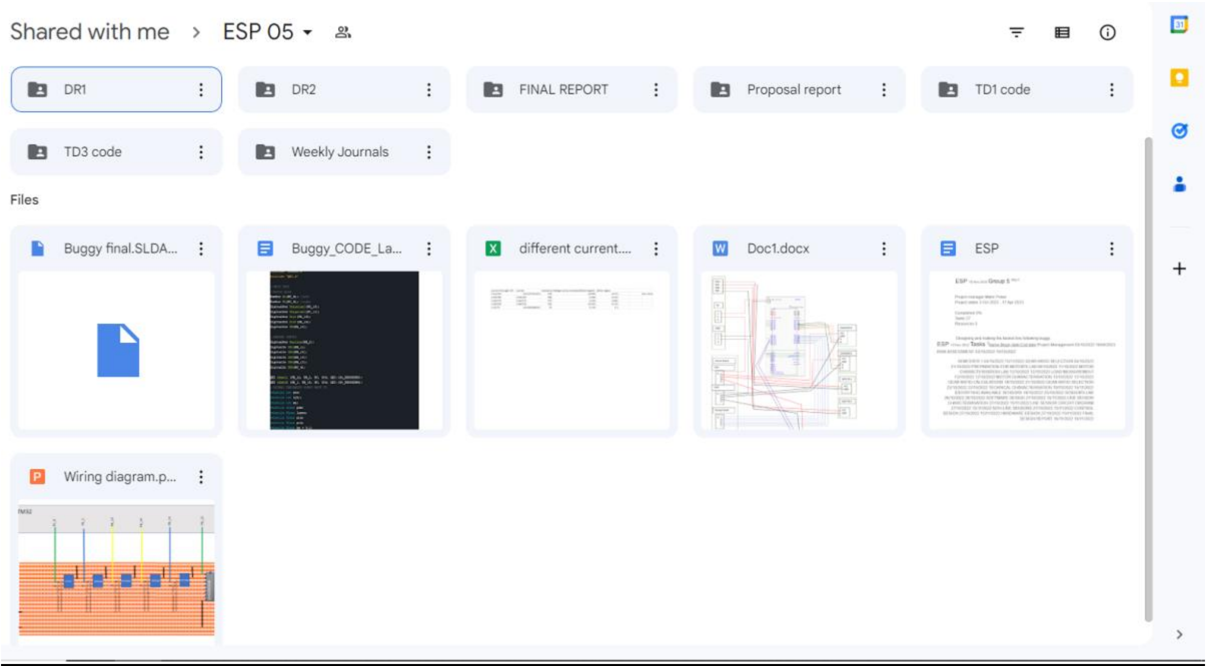

Figure 6: Screenshot of shared google drive.

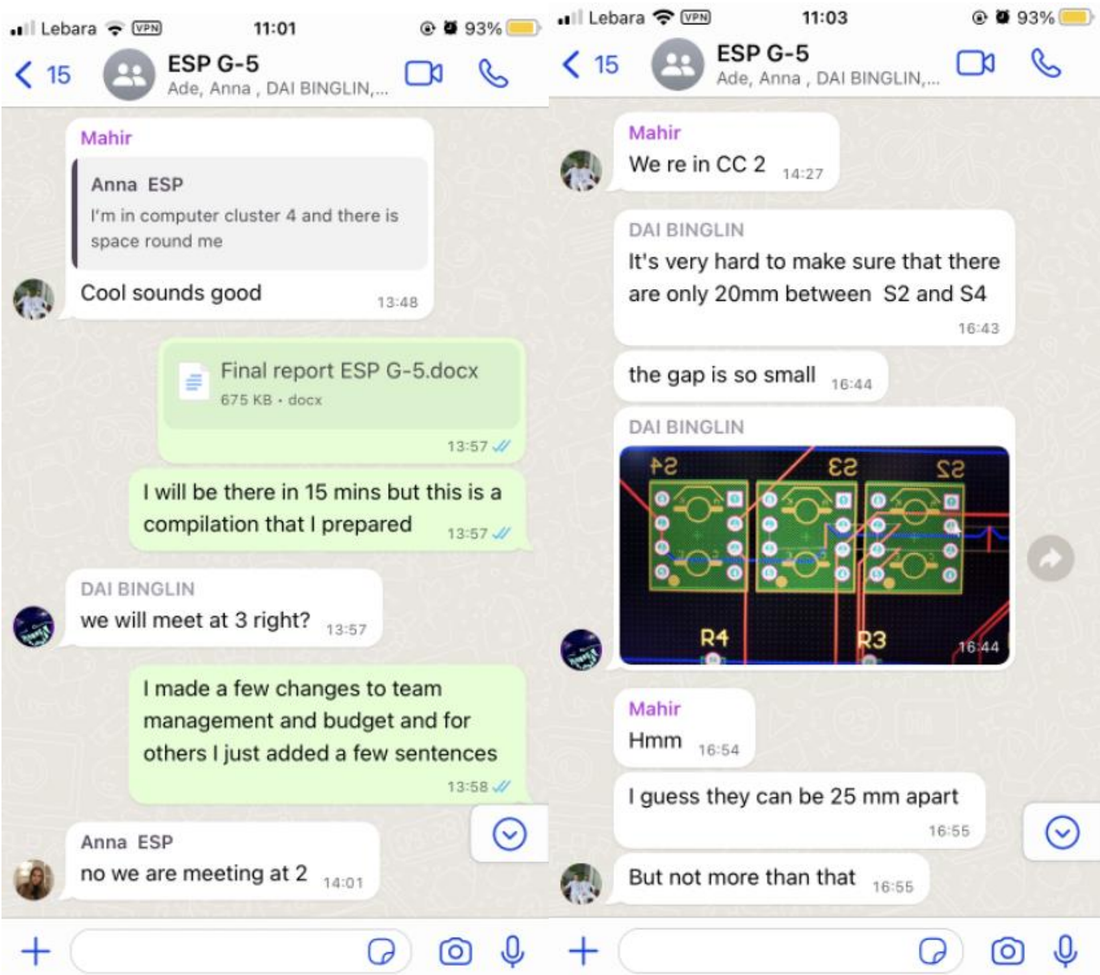

Figure 7: Team communication using WhatsApp.

4. Budget vs Outrun

An essential part of project management is financial management and making sure that the team stays within budget whilst accomplishing all the tasks. According to the proposal document, the total cost of the buggy was expected to be £154.33 [1], which included the free components. This figure was redeveloped in the development phase. The sensors were fragile, two were destroyed during construction. The chassis had to be redesigned as the first iteration could not house the desired sensor board. The PCB had to be re-fabricated as the first one was erroneous. But fortunately, the parts which needed replacement were provided by the department and the team wasn't required to spend the available budget of £40. The free issue components were more than enough at every stage of development and the laboratory facilities for redesigning were also adequately available and easily accessible. This allowed the team to save a lot of time and effort that would have been spent in ordering and receiving components.

Approximating the selling price of the buggy would take into consideration several factors like the material costs, labour costs i.e., the programming wiring, soldering, etc, shipping costs (if any) and lastly a margin of profit. The material cost of the buggy can be estimated to be £190. The time and resources spent in developing the buggy is the sunk cost, which includes the labour cost and additional overheads. These will be recovered during the lifetime of the product. Assuming a standard product lifecycle, £250-260 would be an appropriate price considering a margin of profits and depending on any shipping costs incurred.

5. Analysis of Heats [1]

Finally coming to the most important practical aspect of the embedded systems project is the final heats or the Technical Demonstration 4. During this, the buggy is expected to complete a short test track autonomously. Coming into heats, the buggy had the potential to complete the track autonomously in a decent time. But the speed encoders suffered a mechanical failure two days prior to the heats. To mitigate this fault the code was altered to remove the speed control aspects and navigate through the track according to this change. To ensure the working of this the buggy was tested on an improvised paper track and calibrated accordingly for completing the requirements of the TD-4 and the buggy successfully accomplished that. Figure 8 shows the picture of the improvised track.

Unfortunately, during the final heat demonstrations, the buggy could not complete the track in the first run. In the first run, it started with severe oscillations, made the first left-hand turn but stopped soon after it. This was unexpected given the previous test results. Assuming the problem was due to a change in friction between the test track and the heats track (due to a difference in material) the PID coefficients were re-evaluated, but this did not fix the issue and the buggy didn't navigate efficiently.

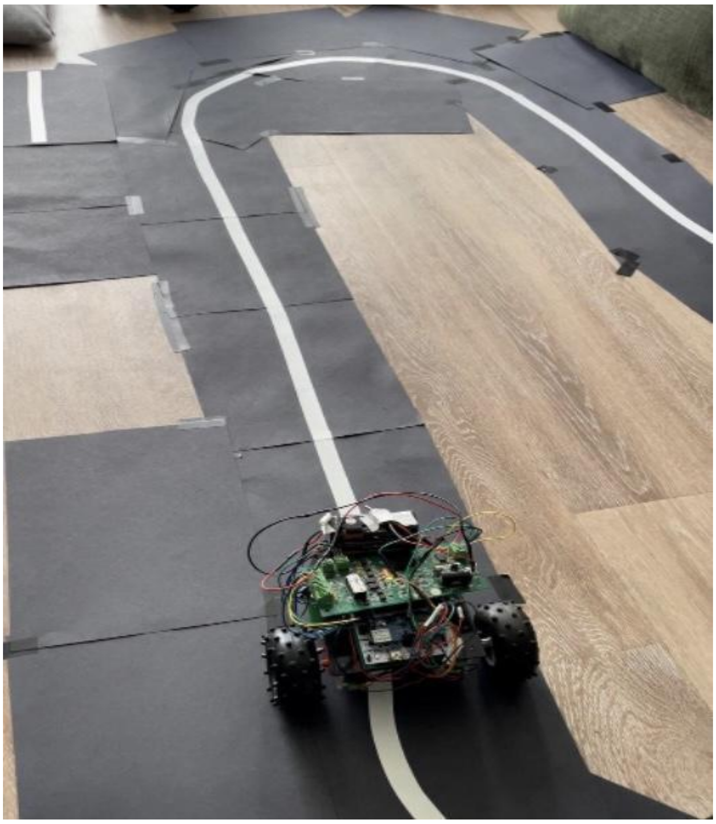

Figure 8: Designed paper trach for testing

The second run ended shortly due to the buggy stopping on the first straight and not proceeding further. Eventually, it was discovered that this was a result of a wiring issue. Upon inspection and further analysis, it was discovered that the actual reason for the deviated performance since the first run was the failure of two sensors, sensors two and four. The buggy was prepared with only one spare sensor, so the pair could not be replaced. Thus, to complete different sections of the track individually the sensors were rearranged such that the outer sensors were removed, and the three working sensors were fitted in the middle slots. The code was altered accordingly to rely upon three sensors, and consequently, the speed of the buggy was reduced as well to ensure that the buggy didn't go off track. The buggy was then able to complete the track in sections, but due to extreme vibrations and oscillations the wiring came undone, and the buggy failed the controlled stop.

Overall, the buggy's construction lacked robustness, due to several errors during the building phase the buggy chassis and PCB had to be redesigned. The PCB redesigning compromised valuable testing time and the buggy's wiring was compromised as well. But the control algorithm was well constructed and reliably implemented given the buggy was able to run with 3 sensors and no speed control with minor changes. This feature allowed the team to compensate for the failures caused due to its robustness up to an extent.

6. Summary

Overall, the embedded systems project aimed to develop an understanding of the integration of the hardware and software concepts of an embedded system and as a result the team developed a white-line following buggy which could function autonomously. The complete assembly included the integration of several mechanical, electronic, control and software components which included the design and development of chassis and sensor board, choosing appropriate sensors and motors according to the track requirements, selection of a suitable control algorithm and finally developing a code to integrate all the above. The team had to redesign the chassis and the sensor board once due to a few failures in the initial design but eventually developed a reliable design.

The team also had strong coordination and communication throughout the project and made sure that each member had equal participation. The members were also considerate of each other's problems and commitments and made sure that everyone was accommodated. It was ensured that everyone's opinions were taken into account before arriving at a decision. The team meetings took place twice a week and a weekly journal was prepared stating individual contributions as a means to communicate with the project supervisor. The team also developed a Gantt chart to create internal deadlines and allocate roles and responsibilities. This was updated throughout the project accordingly. The team made a few mistakes but made sure it wasn't repeated and tried to mitigate them to the best of their capability. By the end of the project, the team delivered several deliverables including reports and practical demonstrations regarding the project.

Apart from these the team ensured to stay within the budget but did incur a few extra expenditures due to faults caused by soldering and redesigning of components.

Towards the end of the project, the buggy performed the final practical demonstration. It did go through a few failures as it was tuned on a different kind of track as compared to the one that was used in the final demonstration but eventually, the code was updated accordingly to make it complete the track in sections.

The embedded systems project as a whole served as a combination of academic and team working experiences and helped each member develop several qualities. It provided essential fundamental concepts of integration of different parts in an embedded system and their practical implementation. Also at the same time, taught the members the aspects of project management including planning, risk management, budgeting, financing, etc.

7. References

[1] Embedded Systems Project (ESP) Group 5, "Proposal Document", University of Manchester, U.K., February 2023

[2] Embedded systems project "Procedures Handbook", Version 2022.2, University of Manchester, U.K., February 2023

[3] ESP Group 5, "Design Report 1", University of Manchester, U.K., 2022

[4] ESP Group 5, "Design Report 2", University of Manchester, U.K., 2022