University of Sheffield

COM2005-3005
Bio-inspired Computing and Robotics

Robotics Lab Assignment

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Robot: A2

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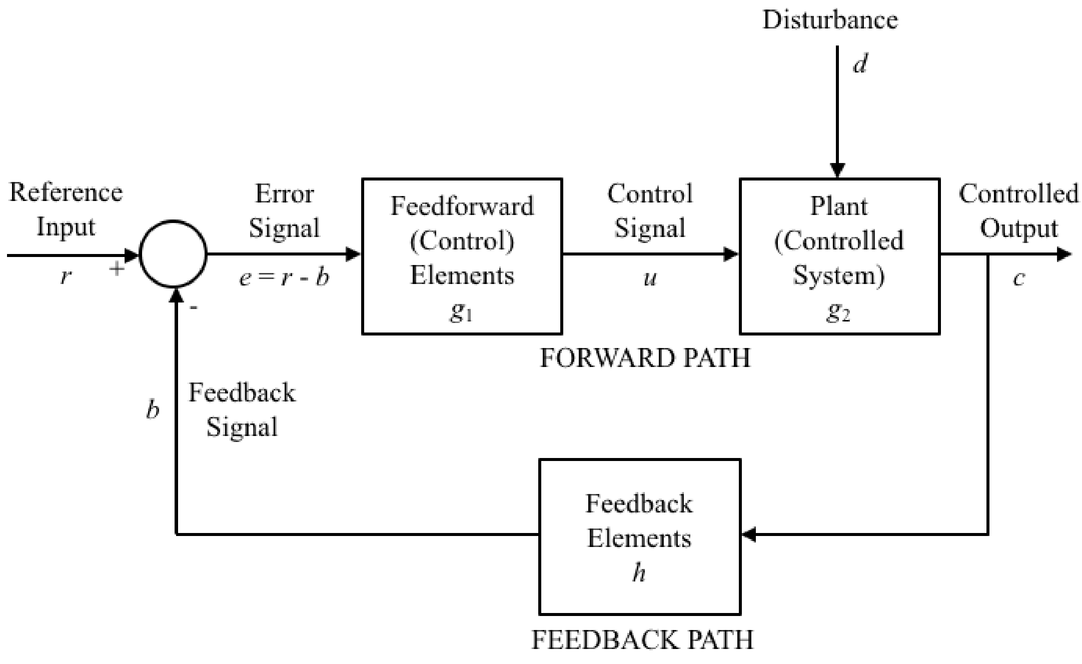
Contents

1 Part I: Experiments with a PID Controller

1.1 General Principles

Recall from Prof. Moore's Lecture-2 on 'Autonomous Systems' that a classic negative-feedback control system is structured as follows:



Recall also that g_1 is commonly configured as a proportional-integral-derivative (PID) controller. Mathematically, this takes the form:

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de}{dt}(t),$$

...where K_P is the proportional gain, K_I is the integral gain and K_D is the derivative gain. A simple proportional controller would use K_P only (i.e. $K_I = 0$ and $K_D = 0$).

In order to ensure that you fully understand these basic principles, please provide brief answers to the following five questions:

Question 1: *What is the function of the 'Reference Input'?* (Worth up to 2 marks)

The reference input is an external signal applied to the feedback control system, usually at the first summing point, in order to command a specific action of the plant. It usually represents ideal or desired plant output behaviour.

Question 2: *What is the significance of* $e = 0$*?* (Worth up to 2 marks)

The *error signal* e is defined as the reference input (r) minus the feedback signal (b). When $e = 0$, it indicates that the control system has reached an equilibrium state, where the reference input applied equals to the feedback signal returned by the feedback elements (sensors etc.). No control action will be carried out by the system unless e is no longer equal to zero.

Question 3: *What is the advantage of a closed-loop configuration over an open-loop configuration?* (Worth up to 4 marks)

1. A closed-loop configuration has better accuracy on its output due to its feedback property, which generates a control signal in order to reduce the difference between the desired value *(reference input)* and actual value *(feedback signal)*. The performance of an open-loop configuration is determined by their calibration, and it is harder to produce consistent outputs using an open-loop configuration by giving different reference inputs. (for example, a toaster machine)
2. A closed-loop configuration is more stable than an open-loop configuration. This is because it will try to maintain the consistency of its outputs by detecting the environmental changes using sensors, and adapting to the changes according to the feedback received to make appropriate control action.
3. External disturbances or noise have reduced effects on a closed-loop configuration. Since a closed-loop configuration relies on a feedback loop, it will try to maintain the consistency of its output by adapting to the changes and generate an appropriate control action. This will reduce the effects of noise, but not entirely eliminate it as noise will still affect the value of the *error signal* compared to one under a noise-free environment.

Question 4: *Give an example of a real-world negative-feedback control system and describe its operation.* (Worth up to 8 marks)

A real-world example would be the cruise control feature on a car, where;

Reference input, r	:	The driver's desired driving speed
Feedback signal, b	:	The current speed of the car measured by the speedometer
Error signal, e	:	The difference between the desired speed and current speed
Control signal, u	:	The required power to be supplied to the motor by the engine

This feature works by the continuously monitoring the difference between the current speed of the car and the desired speed of the car, and adjusting the acceleration accordingly in real time to maintain the car at the desired speed ($e = 0$).

A situation where the acceleration must be adjusted according to feedback received from the external sensor would be when the car is driving on an inclined plane instead on a flat plane.

- When the car is driving uphill, the system will accelerate the car

- When the car is driving downhill, the system will decelerate the car

The system will respond to this feedback by adjusting the acceleration to either give the car less power or more power so that the car maintains a steady speed as set by the driver.

Question 5: *Assuming that $K_I = 0$ and $K_D = 0$, what would happen to your example system if (i) $K_P = 0$ or (ii) $K_P < 0$?* (Worth up to 4 marks)

(i) If $K_P = 0$, assuming that the car has an initial speed and the engine is providing a base power to the motor, then the power output from the engine will remain the same and the speed of the car is fully controlled by the driver. No control actions will be carried out by the system because the 'control signal' u is defined as

$$u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de}{dt}(t).$$

Hence, $u = 0$ if $K_P = 0$, $K_I = 0$ and $K_D = 0$ regardless of the value of the 'error signal' e.

(ii) If $K_P < 0$, then the system would become a positive-feedback control system. When the current speed is higher than the desired speed, the system will keep accelerating instead of decelerating. Conversely, when the current speed is lower than the desired speed, then the system will keep decelerating instead of accelerating. The value of e will only get larger and larger because the *control signal*, u, sent to the motor will have the opposite sign of the correct value. Therefore, the system will have an opposite effect and will perform opposite actions.

1.2 Setting up the Lego EV3 Robot

You have already used the Lego EV3 system in your first-year Java Programming course (COM1003). The EV3 robots are controlled by sending commands over a wireless (Bluetooth) connection from a `Java` program running on a desktop computer. You will use the `ShefRobot` package which provides a simple wrapper of the `Lejos` EV3 library. The relevant resources (including `ShefRobot`) can be found at: `https://staffwww.dcs.shef.ac.uk/people/S.North/campus_only/com1003/robots/index.html`

For COM2005-3005 you will use the Lego EV3 robot in its basic 'tribot' configuration (two driving wheels and a rear trailing wheel) with additional sensors.

Your first practical task is to collect your robot, set up communications between your robot and your computer, and write a simple `Java` program to confirm your ability to control the robot. If you have any difficulties, contact one of the demonstrators. Tick off the following items (by editing the LaTeX source file) when they have been achieved:

☑ Robot collected

☑ Communications established between computer and robot

☑ Able to control robot using `ShefRobot`

Next, mount one of the ultrasonic distance sensors on the front of the robot facing forwards, and test that you can read its sensor values continuously (this will require a processing loop):

- ☑ Sensor mounted
- ☑ Able to receive sensor values

Question 6: *How do the values from the ultrasonic sensor vary as a function of (i) distance to a surface and (ii) surface angle, and how stable are the readings over time?* (Worth up to 8 marks)

(i) The distance is returned in metres by the ultrasonic sensor to 9 decimal places. The maximum range of the ultrasonic sensor is approximately 1.7 m, any distances further than this will be returned as *Positive Infinity.* The readings are consistent and precise if the position of the robot does not change, and the wall is the only object that can be detected by the sensor (no other obstacles or objects around the robot). The ultrasonic sensor is very sensitive, a slight change in position can give different reading. As shown in **Table 1** below, the ultrasonic sensor is tested to be accurate to have a maximum 3.34% of error margin. The actual distance was measured using a 15 cm ruler.

Actual Distance (cm)	Reading from Ultrasonic Sensor (m)	Percentage error (%)
1.0	0.009804731	1.96
3.0	0.031003194	3.34
5.0	0.050919810	1.84
10.0	0.101000587	1.00
12.0	0.120132807	0.11
15.0	0.149061548	0.63

Table 1: Variation of ultrasonic sensor values as a function of distance

(ii) The field of view of the ultrasonic sensor is tested to be approximately 50°. Readings from difference surface angle are tested by placing the robot 12 cm away from the wall, measured from the centre of the sensor using a ruler. The offset of the surface angle is measured from the centre of the field of view of the robot when it is facing perpendicularly to the wall.

Surface Angle to the left (°)	Reading from Ultrasonic Sensor (m)	Percentage error (%)
0	0.120041684	0.03
15	0.122061947	1.72
30	0.125694161	4.75
45	0.133551984	11.29
60	0.171919487	43.27
90	Infinity	100.0

Table 2: Variation of ultrasonic sensor values as a function of

surface angle to the left from the centre of the field of view

Surface Angle to the right (°)	Reading from Ultrasonic Sensor (m)	Percentage error (%)
0	0.120041684	0.03
15	0.122132148	1.78
30	0.125684165	4.74
45	0.136981197	14.15
60	0.186565197	55.47
90	Infinity	100.0

Table 3: Variation of ultrasonic sensor values as a function of surface angle to the right from the centre of the field of view

The reference point of 0° was chosen to be where the robot is perpendicular to the wall that we are observing. **Figure 1** displays the angles tested in order to gather the data required from the sensor. According to the results obtained in **Table 2** and **Table 3**, the readings returned by the ultrasonic sensor become less accurate when the surface angle deviation becomes larger. The readings returned by the ultrasonic sensor are most accurate when the sensor is facing perpendicularly to the wall. This can be explained by the emitter sending out pings from the left lens, then being reflected by the wall directly back to the right receiver lens. When the ultrasonic sensor is facing perpendicularly to the wall, the left lens and right lens have the same distance to the wall, hence, the value returned by the sensor is the shortest distance between the sensor and the wall. When the sensor is facing 45° to the left, the left lens is farther and the right lens is closer to the wall, hence, the distance returned by the sensor will be shorter compared to the distance returned when it is facing 45° to the right.

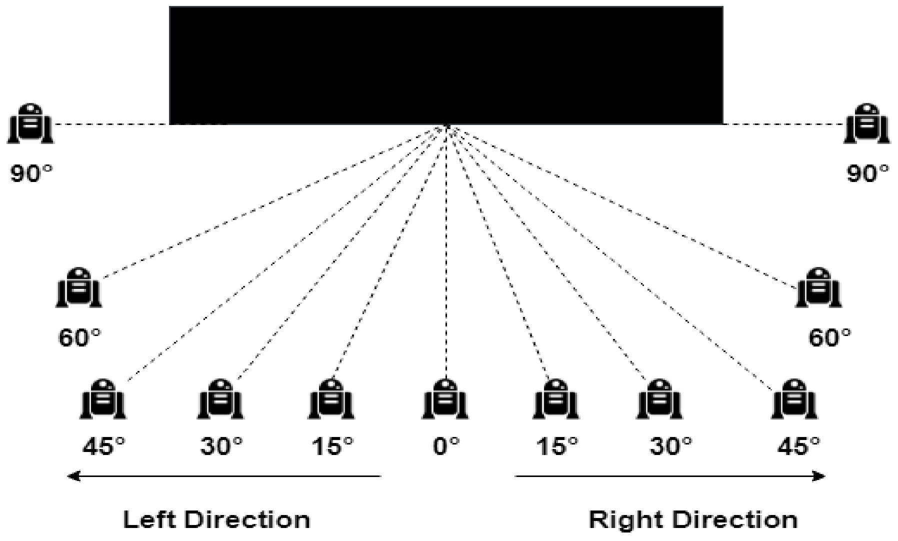


Figure 1: Change of angle between the robot and the surface it is observing

1.3 Basic PID Controller

The next step is to program the robot to position itself *autonomously* at a set distance from a vertical surface (such as a wall). In order to do this you will need to implement a closed-loop negative feedback system incorporating a PID controller. The 'reference input' r corresponds to the desired distance between the robot and the surface, the 'feedback signal' b corresponds to the output of the ultrasonic distance sensor, and the 'control signal' u corresponds to the value that is sent to the motors. The PID controller should be of the form $u(t) = K_P e(t) + K_I \int e(t)dt + K_D \frac{de}{dt}(t)$ (as indicated earlier).

Note: *You will have to measure dt (the loop time) using the system clock.*

Note: *Be aware that the* `Lejos` *EV3 library has separate commands to make the motors go forwards or in reverse. This means that you will have to convert +ve and −ve control signals into suitable motor commands.*

Once you have implemented the code, you should follow these steps:

1. Set $r = 50cm$.
2. Set $K_P = 1$, $K_I = 0$ and $K_D = 0$.
3. Place the robot 100 cm from a vertical surface with the ultrasonic sensor facing towards it.
4. Run the code.

If all is well, then your robot should move slowly towards the surface slowing down and eventually stopping as it approaches the 50 cm point.

Note: *If your robot appears to do the opposite of what you expect, try setting $K_P = -1$. If that solves the problem, then you have implemented a positive-feedback rather than a negative-feedback loop. This means that you need to swap the polarity of the signal being sent to the motors (and reset $K_P = 1$).*

Tick the following when your robot behaves correctly (by editing the LaTeX source file, as before):

☑ Robot behaves as expected

Question 7: *With the code still running, what happens if, after the robot has arrived at the 50 cm point, you manually push it towards the surface?* (Worth up to 2 marks)

The robot will move backwards if it is manually pushed past the 50 cm point. The speed of the robot moving backwards is directly proportional to the distance between the robot and the 50 cm point after it has been pushed past the point, i.e. the robot will move backwards faster if it is closer to the surface, and slower if it is far away from the surface and closer to the 50 cm point.

Now implement an outer loop that swaps r between 30 cm and 50 cm every 10 seconds. As a result, your robot should now change its position at regular intervals. These step changes in r will make it easier to observe the robot's behaviour for different values of K_P, K_I and K_D.

Question 8: *With $K_I = 0$ and $K_D = 0$, what happens when you experiment with different values of K_P? In particular, (i) what is a 'good' value for K_P (and why), (ii) what value of K_P causes the robot to start to oscillate continuously backwards and forwards around the target r, and (iii) when it starts to oscillate continuously, what is the oscillation period? Hint: start with $K_P = 1$, then increase it gradually.* (Worth up to 5 marks)

(i) A 'good' value of K_P is the optimum value that allows the robot to arrive to the reference point quickly and accurately without overshooting and oscillating around the reference point. Any values lower than the 'good' value will cause the robot to have higher stability, reaching the reference point more precisely at the cost of slower speed. Values larger than the 'good' value will cause the robot to arrive quicker at the reference point, but the robot will have decreased stability where it will overshoot and have to correct it's position to arrive at the reference point. According to our experiment, $K_P = 75$ is a 'good' value for our robot configuration.

In the maze running competition, it might be better to use a slightly lower value of K_P than the 'good' value. This is because there is a slight delay in the WiFi connection between the robot and the computer. Hence, a slightly lower K_P value will make the robot move slower and more stable as specified above. Also this can prevent the robot from running into the wall in the case of a short connection issue that is encountered throughout the run.

(ii) We have experimented several values of 'high' K_P to find out the 'ultimate gain'.

- When $K_P = 103$, the robot started to oscillate slowly around the reference point, but it eventually converged and stopped.
- When $K_P = 125$, the robot oscillated consistently around the reference point.
- When $K_P = 155$, the robot oscillated heavily around the reference point, the oscillation distance became larger and larger overtime.

Hence, our 'ultimate gain' $K_U = 125$.

(iii) When $K_P = 125$, the robot oscillated 7 times in 10 seconds. Therefore, the oscillation period T_U is $\frac{10}{7} = 1.4286$ secs.

The value of K_P that causes the robot to oscillate backwards and forwards continuously is known as the 'ultimate gain' K_U, and the oscillation period is designated as T_U.

Note: *Be aware that T_U is a measure of time, not frequency. I.e. if the robot oscillates backwards and forwards at a rate of five times a second, then $T_U = 1/5 = 0.2$ secs.*

Question 9: *What is the relationship between the 'good' value of K_P that you discovered by experimentation and the value of K_U that you measured?* (Worth up to 5 marks)

The value of K_U is much higher than the 'good' K_P value. This is because the value of K_P is inversely proportional to the stability of the robot. Assuming K_I and K_D are zero, when the value of K_P would be very small, the robot would move very slowly towards the reference point and stop exactly when it reaches the reference point. The 'good' value of K_P that we discovered is a compromise between speed and accuracy so that the robot reaches the set reference point quickly enough stopping on the reference point accurately without oscillating. Our K_U shows the point where the compromise mentioned previously is more inclined towards the speed of the robot, so the robot reaches the reference point very fast but will not be able to precisely stop at the required distance so it will start to oscillate back and fourth around it.

1.4 PID Tuning

There are several methods available for tuning the parameters of a PID controller. The *manual* method involves setting $K_P = 0.5K_U$, $K_I = 0$ and $K_D = 0$. Next, K_I is gradually increased to improve the convergence. Then K_D is gradually increased to improve the responsiveness.

A more formal tuning approach is known as the *Ziegler-Nichols* method. Once K_U and T_U have been determined, the PID gains may be set according to the following heuristic:

	K_P	K_I	K_D
P	$0.5K_U$		
PI	$0.45K_U$	$0.54K_U/T_U$	
PID	$0.6K_U$	$1.2K_U/T_U$	$3K_UT_U/40$

Question 10: *What values of K_P, K_I and K_D are given by the Ziegler-Nichols method for a P, PI and PID controller (based on the values of K_U and T_U you measured previously)?* (Worth up to 5 marks)

When $K_U = 125$ and $T_U = 1.4286$,

	K_P	K_I	K_D
P	62.5		
PI	56.25	47.2491	
PID	75	104.9979	13.3931

Table 4. Values of K_P, K_I and K_D for a P, PI and PID controller using Ziegler-Nichols method

The values of K_P, K_I and K_D given by the Ziegler-Nichols method do not give perfect results on our robot. We were required to perform a manual tuning process on K_P, K_I and K_D by trial-and-error. According to our experimentation, the values of K_P and K_I given by Ziegler-Nichols method were too high. Using the values of K_P, K_I and K_D in **Table 4** caused the robot to speed up and stop suddenly at certain point. Although the robot moved quickly to the target, its movement was too unpredictable that it would be risky to use these values in the maze competition.

We managed to get the optimal values of K_P, K_I and K_D for our robot by lowering K_P and K_I drastically, and changing the formula we used to set the speed of the motors. Since we converted the distance returned by the sensors to centimetres, we are required to apply a multiplier to one of the motors in order to make the robot turn effectively. The final values are $K_P = 40$. $K_I = 10$ and $K_D = 13$.

Confirm the effectiveness of the Ziegler-Nichols method by setting the values for K_P, K_I and K_D in your controller, and tick the following:

☑ The robot moves quickly to the target and stops with minimal overshoot

Question 11: *Using the values for K_P, K_I and K_D given by the Ziegler-Nichols method, what happens when you decrease the sampling rate (e.g. by introducing a 'wait' function in the loop)? What is the significance of your observations?* (Worth up to 5 marks)

Using the values for K_P, K_I and K_D given by the Ziegler-Nichols method above, **Table 5** below shows the experimented wait periods and their result.

Wait period (second)	Result
0.1	The robot was still able to function accurately. It might slightly overshoot the reference point, depending on the initial distance between the robot and the reference point, but the difference between a continuous sampling rate is hardly noticeable.
0.2	The overshoot was more obvious, but the robot reached the reference point slightly quicker due to the delay in the speed change. The robot started to oscillate slowly around the reference point after it reached it, and eventually converged. It is still considered as functioning.
0.3	The robot reached the reference point quicker than the previous setting, but the overshoot became worse. The oscillation becomes larger and inconsistent. The control quality of the robot starts to degrade.
0.4	The robot maintained its initial speed until it was very close to the reference point, and the sudden change of the speed is obvious. The overshoot and oscillation was more inconsistent than the previous setting.
0.5	The robot will always overshoot the reference point. The distance between the robot and the reference point was always different when the wait period was over.

Table 5: Experimentations of different wait periods and their results

Introducing a 'wait' function in the loop had a negative effect on the performance of our robot and degraded the control quality. This is due to the fact that we have decreased the sampling rate and the robot had less values to work with. During the 'wait' periods, the robot is not receiving the feedback from the sensors, hence, its state (moving or stationary) would not be changed because no control signal is produced during the 'wait' periods. Therefore, it would be unaware of its position for a longer period of time, making it more likely to overshoot the set reference point and oscillate around it. In order to increase the control quality of our PID controller we have to adjust the K_P value so that the decrease in sampling rate will be accounted for.

According to our experimentations for a 0.1 seconds wait period, the 'ultimate gain' K_U is now 120. The robot oscillated 13 times in 20 seconds, so the oscillation period T_U is $\frac{20}{13} = 1.5385$ secs. Hence, the values for K_P, K_I and K_D with a 0.1 seconds wait period are

	K_P	K_I	K_D
P	60		
PI	54	42.12	
PID	72	93.6	13.8462

Table 6: Values of K_P, K_I and K_D for a P, PI and PID controller using Ziegler-Nichols method when the wait period is 0.1 seconds

According to the table above, it can be stated that the values of K_P, K_I decreases and K_D increases as the wait period increases.

In the maze running competition, it is best to use the highest sampling rate available. This is because the surroundings of the robot change too frequently. The robot needs to maintain the distance between itself and two walls, and also needs to turn accordingly when there is a curve in the maze.

1.5 PID-based Steering

Finally (for Part I), reposition your ultrasonic sensor so that it faces sideways from the robot.

Now re-program your robot with a PID controller that maintains a fixed distance from a wall as the robot travels along parallel to it. This will require the speed to be set at some fixed value, and the PID-based control loop will handle the steering. Use the Ziegler-Nichols method to determine appropriate values for K_P, K_I and K_D (this can be done while the robot is stationary and changing the target distance a few centimetres once every 10 seconds, as before).

Note: *It is particularly important that the sensor is mounted well forward of the driving wheels, otherwise it will not be sensitive to changes in direction when the robot is stationary.*

Question 12: *What values for K_U and T_U did you measure, and what are the resulting values for K_P, K_I and K_D given by the Ziegler-Nichols method?* (Worth up to 5 marks)

We have set the base speed of the robot as 200 and positioned the ultrasonic sensor at the left side of the robot. We measured the value of K_P using this setting.

The 'good' value of K_P measured was 83, and the 'ultimate gain' K_U measured was 140. The robot oscillated 8 times in 5 seconds, hence the oscillation period T_U is $\frac{5}{4}$ = 1.25 secs.

When $K_U = 140$ and $T_U = 1.25$,

	K_P	K_I	K_D
P	70		
PI	63	60.48	
PID	84	134.4	13.125

Table 7: Values of K_P, K_I and K_D for a P, PI and PID controller using Ziegler-Nichols method for left wall steering

Similar to **Question 10**, these K_P, K_I and K_D values given by Zielger-Nichols method did not produce satisfying result. The robot turned too quickly to right when it passed the reference value, and turned too quickly back to left again, causing the robot to move in a snake-like movement.

Confirm the effectiveness of these values for K_P, K_I and K_D, and tick the following:

- [✓] The robot travels along a wall maintaining a constant distance from it

1.6 Summary

You have successfully completed Part I of the assignment, and you should now have all of the skills necessary to move on to Part II.

2 Part II: Maze-Running Competition

2.1 Objective

The aim of Part II of the assignment is to combine the theoretical knowledge you have obtained in the lectures with the practical experience you have acquired in Part I to design and implement a robot that is capable of competing in a simple maze-running competition.

The challenge is to navigate a corridor (that will be set up in the robot arena) in the fastest time possible and without touching the walls. The precise layout will not be revealed until the final lab session. However, you will be able to practice in the arena beforehand. The two walls of the corridor are painted different colours so that, if necessary, your robot can determine if it is going in the correct direction.

You need to decide which control principle(s) to use and how to set up your robot's sensors and actuators. Also, since it's a competition, you will need to to think about how your robot manages 'risk', i.e. is it better to be slow-and-careful or reckless-but-fast? You will probably need to experiment with various alternatives before deciding on a final approach.

Note: *You will need to adopt good working practices for (i) organising your team and (ii) software version control. The latter is important as robots are notorious for failing after a so-called 'improvement', so being able to revert easily to an earlier version will save a lot of pain and grief.*

Note: *Each Lego kit contains two ultrasonic sensors.*

Note: *The maze will be a simple winding corridor. There will be no dead-ends, no loops and no junctions. However, there may be chicanes and small breaks in the wall.*

2.2 The Competition

In order to give every team an equal chance, the competition will be organised into a number of leagues, each consisting of several teams (and their robots). Marks will be awarded based on each robot's performance **within its league**. This will mean that each team will be competing against teams that have had an equal amount of time devoted to the development of their respective robots. The competition will take place during the final lab session.

Note: *If there is time at the end of the league battles, the winning robot in each league will compete again to find the overall champion. This 'championship' contest will not count towards the marks for the assignment, but a (small) prize may be awarded.*

As you can imagine, running such an event with a large number of teams/robots requires very precise time management, so we will be issuing a strict timetable for the final lab session. This should appear on MOLE the week before. It is essential that you prepare carefully for your designated time slot (otherwise you may lose marks - see below).

The rules for the competition are as follows:

1. Any number of practice runs may be made (subject to the availability of the arena).
2. Each team must register their arrival at the arena (with their robot) 10 mins prior to their league's designated time slot, after which no further technical development

will be permitted.

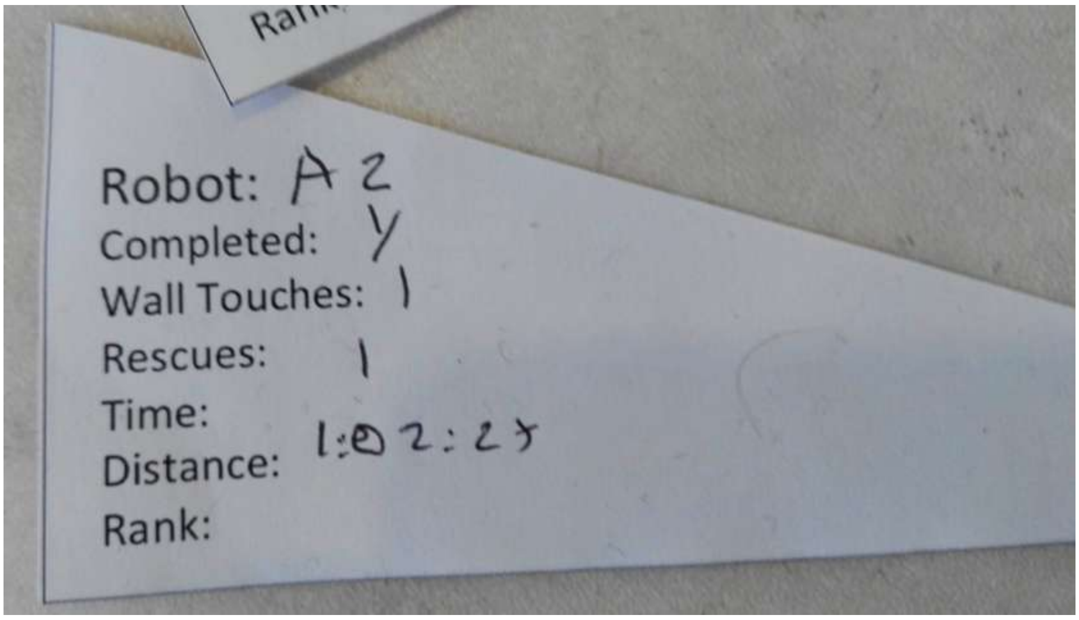
3. Each team will be called forward in turn to place their robot on the starting line.
4. An ‘official’ run for each team’s robot will be timed by the lab demonstrators.
5. If a robot fails to complete a run within a **3 minute time limit**, the demonstrators will record the furthest position it reached.
6. It is permitted for a designated team member to rescue their robot and place it back on the course at the place where things went wrong **twice** per run without penalty, but the clock will keep running. A third rescue is not permitted, instead the run will be terminated and the position reached will be recorded.
7. Failure to arrive at the arena at the designated time will earn a penalty (see below) and may mean that you do not get a run.

Marks will be awarded as follows:

- 5 marks will be awarded for a run completed within the 3 minute time limit.
- 5 marks will be awarded for a ‘clean’ run. (i.e. no walls touched and no rescues).
- 10 marks will be awarded to the team with the best run within their league, 9 marks to the second best team, and so on. A team who fails to arrive at the arena at their designated time will be ranked last in their league.

Question 13: *What was the result of your official attempt?* (Worth up to 20 marks)

Completed	**Wall Touches**	**Rescues**	**Time**	**Distance**	**Rank**
Y	1	1	00:01:02	10.5 metres	2nd


Ran

Robot: A 2
Completed: Y
Wall Touches: 1
Rescues: 1
Time:
Distance: 1:02:27
Rank:

Our actual score is 00:01:17 with the time penalty added due to rescue and wall touch.

2.3 Your Team's Solution

Question 14: *In terms of your robot's software architecture, what principles did you explore, and what was the final approach taken (include a system diagram)?* (Worth up to 15 marks)

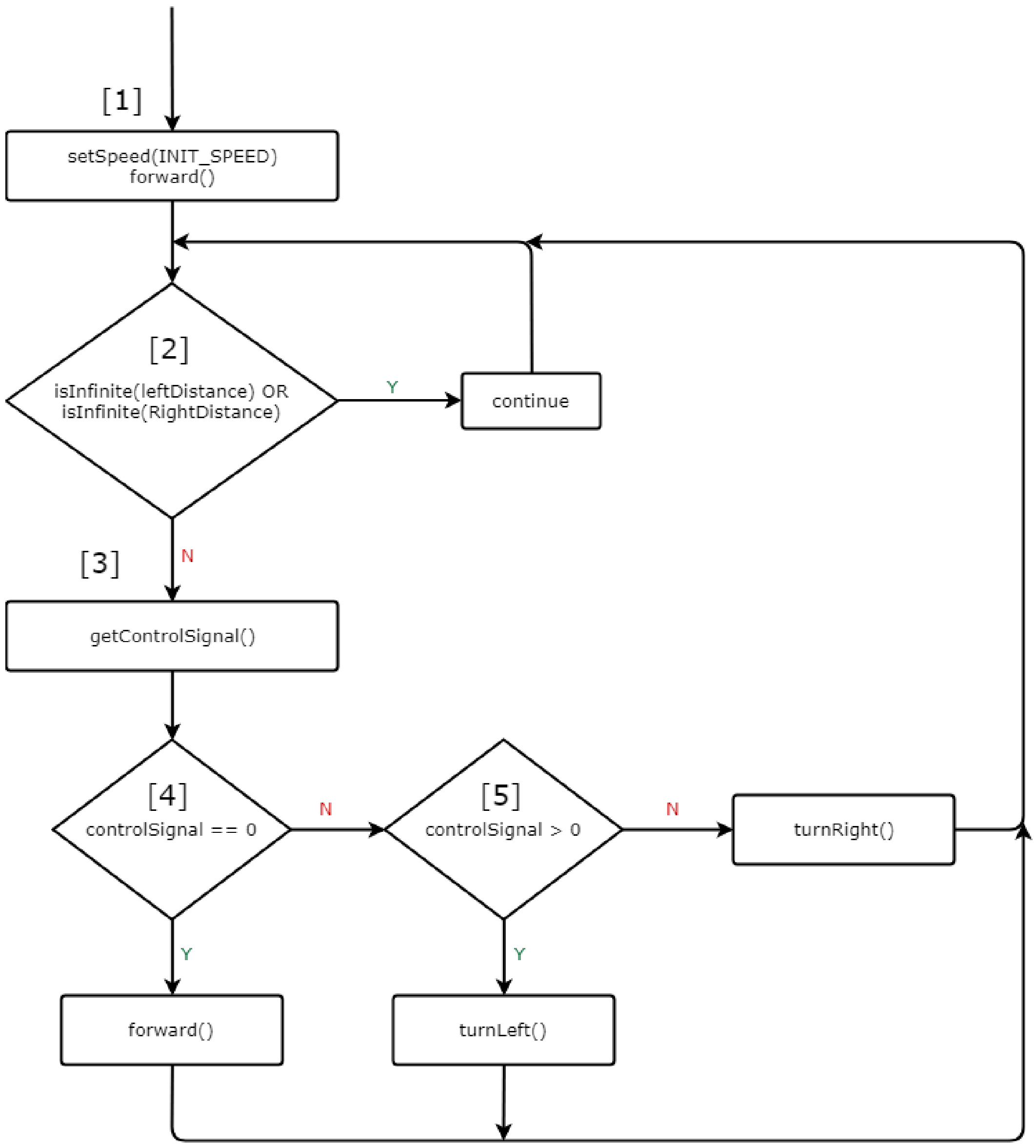


Figure 2. Flowchart of our robot control loop

1. Step [1]: Before entering the loop, the initial speed of the robot is set at a fixed value and it is set to move forward.
2. Step [2]: If the left sensor or the right sensor detects an *Infinity* distance, the control loop is skipped and the robot will continue its last action (forward, turn left, or turn right)
3. Step [3]: Our 'error signal' e is defined as *leftDistance* - *rightDistance*, where *leftDistance* is the distance returned by the left sensor and vice versa. The

formula for calculating the ‘control signal’ u is:

$$(K_P \times \text{error}) + (K_I \times \text{integral}) + (K_D \times \text{derivative})$$

where integral $= \frac{2}{3} \times$(integral + error), derivative = error - lastError

4. Step [4]: If the control signal $u = 0$, then the robot should move forward.
5. Step [5]: If the control signal $u > 0$, which means *leftDistance* > *rightDistance*, then the robot should turn left. Else the robot should turn right because *leftDistance* < *rightDistance.*

Our final system design is shown in **Figure 2**, showing the decisions robot continuously loops through. It sees which direction it needs to turn by comparing the *leftDistance* and *rightDistance* in order to find an equilibrium between the two walls, adjusts its course to do so, then loops again to smoothly make its way through the course. In the case of detecting an *Infinity* value, the robot will continue its last action as it is unable to determine whether that is just a disturbance or a sharp turn. Overall, this final approach is more stable and practical than having multiple *if else* statements in the code to control the robot actions.

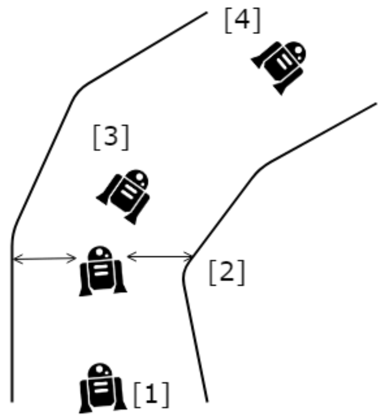


Figure 3: Robot movement for a turn in final our implementation

As shown in **Figure 3**, our final implementation will allow the robot to maintain an equal distance between the left and right wall. At [**1**], the robot will be moving forward since the left and right sensor detected the same distance. At [**2**], the *rightDistance* is now larger than the *leftDistance.* According to the control loop, the control signal u is now less than 0, so the robot should be turning right. At [**3**], after the robot has turned right, it will try to maintain an equal distance between the left and right wall again. At [**4**], the robot has completed the turn, everything is back to the same state as [**1**] again.

At first, we investigated a variety of PID controller implementations in order to gather a better insight as to what would be the best approach for our specific scenario. From our research we established that our implementation would consist of trying to maintain an equilibrium between a set reference point and the wall. By doing this we would attempt to follow one of the walls the whole way round the maze to get to the end. After experimenting with a few difference distances from the wall it was found that sometimes this approach did not work correctly. When following a wall, the robot would get stuck when the angle was less than 90° or there was a very sharp turn. This was due to the fact that the robot was not able to predict the turn because of the software implementation and because it uses an input only to sense the distance to the side wall and and has no real knowledge of anything ahead. Using **Figure 4** we can envisage the scenario better and show that when the angle of the turn is less than 90°, the robot will be unable to take the turn using this method.

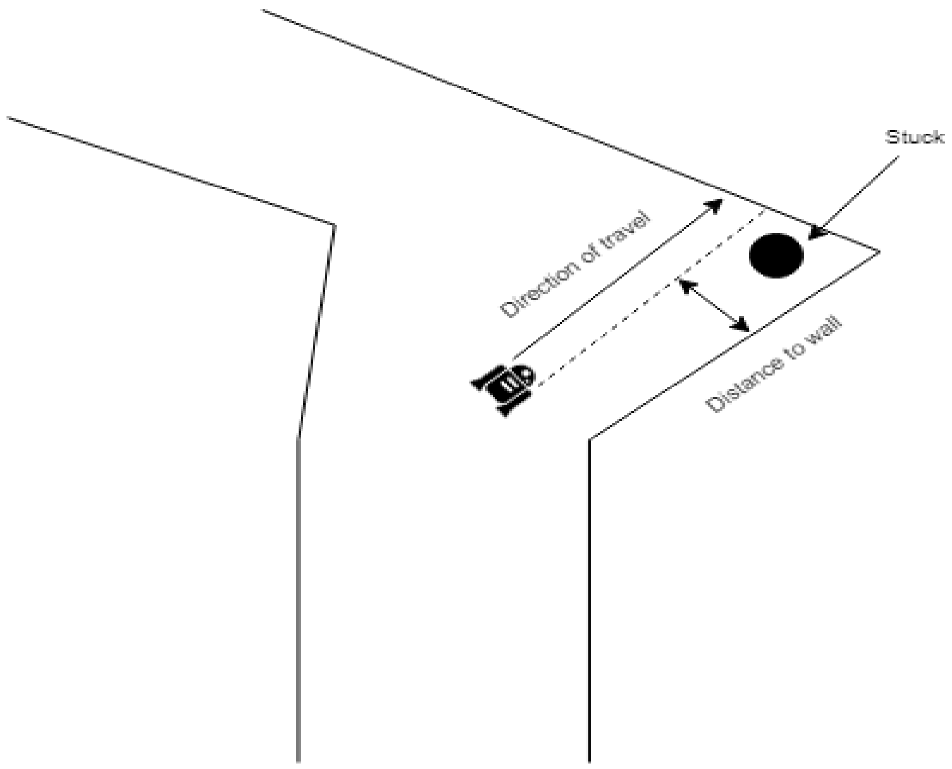


Figure 4: First implementation attempt

Originally in **Step[5]** of **Figure 2**, we implemented a function that compared the last distances returned and the current distance returned by the sensors. For example, if the difference between the *lastDistance* and *currentDistance* returned by the left sensor exceeds a certain threshold, then the robot knows that it has reached a sharp turn, and it should keep turning left until the control signal becomes 0. Theoretically, this approach should prevent the case where the robot does not turn enough in a sharp turn. However, due to the delay in the WiFi connection, the lag in readings received caused the robot to continue turning for too long, hitting the wall.

Our second approach was to change our implementation slightly and attempt to monitor the distance between the left and the right walls simultaneously. Using this method, displayed in **Figure 5**, we tried to keep the robot in between the two walls by keeping the difference between the distances of the robot and each of the two walls at 0 throughout the run in the maze. This approach turned out to solve the problem that we encountered previously, therefore now even if our robot encounters a very sharp turn it will be able to cope with it. This is because the robot will never be too close to the wall at any point which will allow plenty of time and distance to complete the turn for any sharp corners encountered. The only slight problem with this approach was that using the previous values for the configuration of the PID Controller would not work anymore. Therefore in order to solve this we had to experiment further so that we can find the correct PID configuration variables.

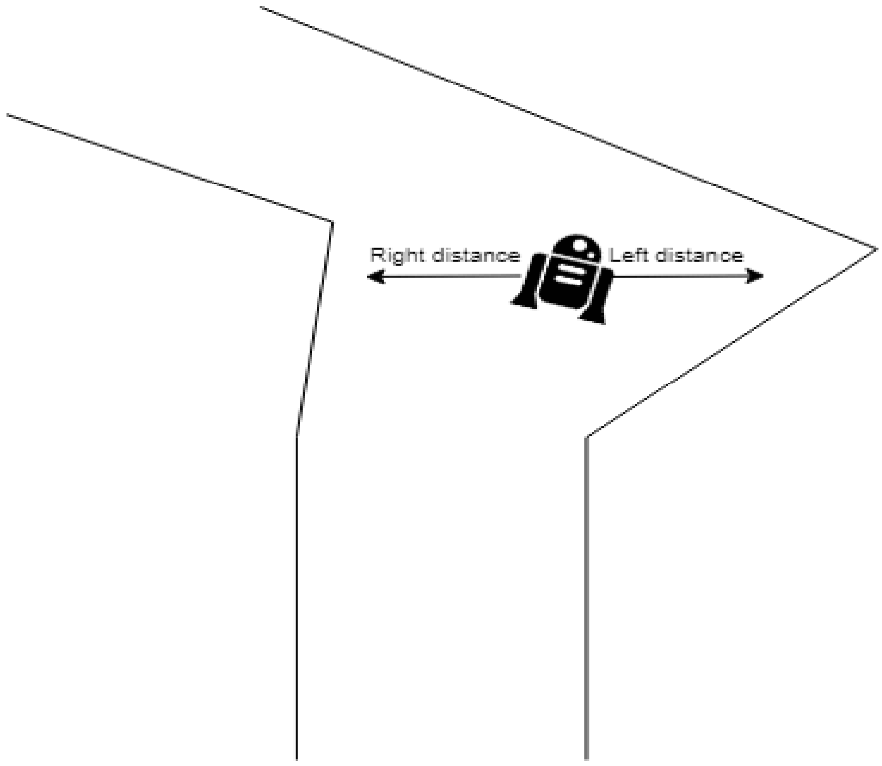


Figure 5: Second implementation attempt

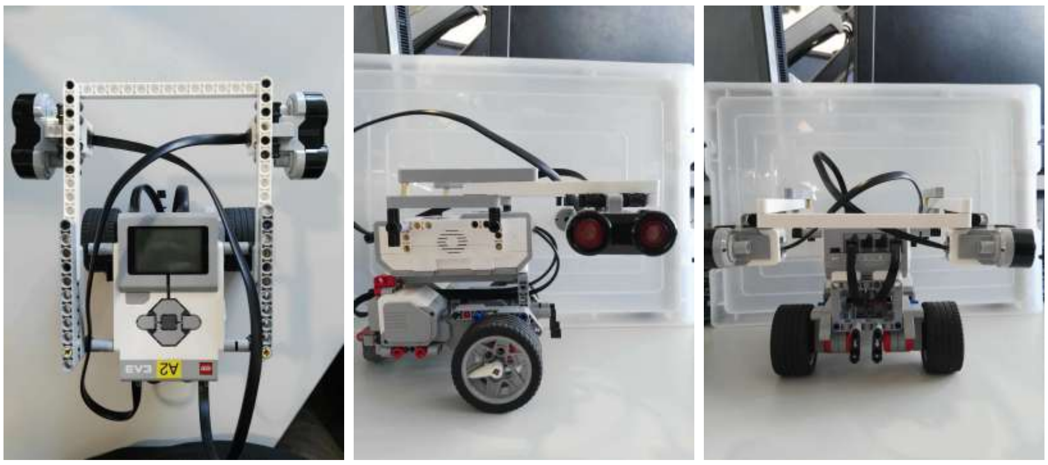


Figure 6: Horizontal sensor configuration (first prototype)

Figure 6 showed our first prototype, which is a horizontal positioned sensors in left and right direction. This prototype is very good at following a straight line but it is not capable of making a turn effectively.

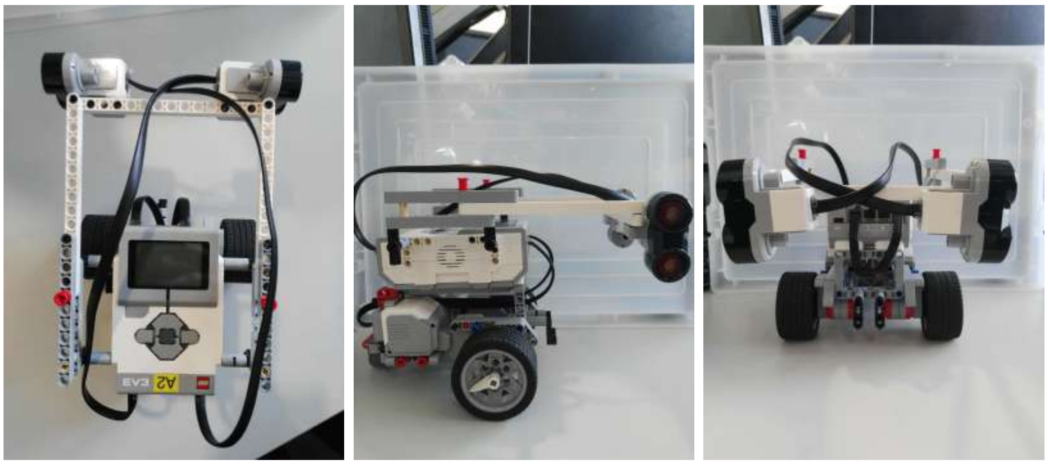


Figure 7: Vertical sensor configuration (second prototype)

Figure 7 showed our second prototype, which is similar to the first prototype, but the sensors are positioned vertically. The second prototype has a more restricted horizontal viewing angle compared to the first prototype. According to our experimentation, the second prototype showed no noticeable improvement in the maze.

Question 15: *What was your robot's final physical configuration (include a photo)?* (Worth up to 5 marks)

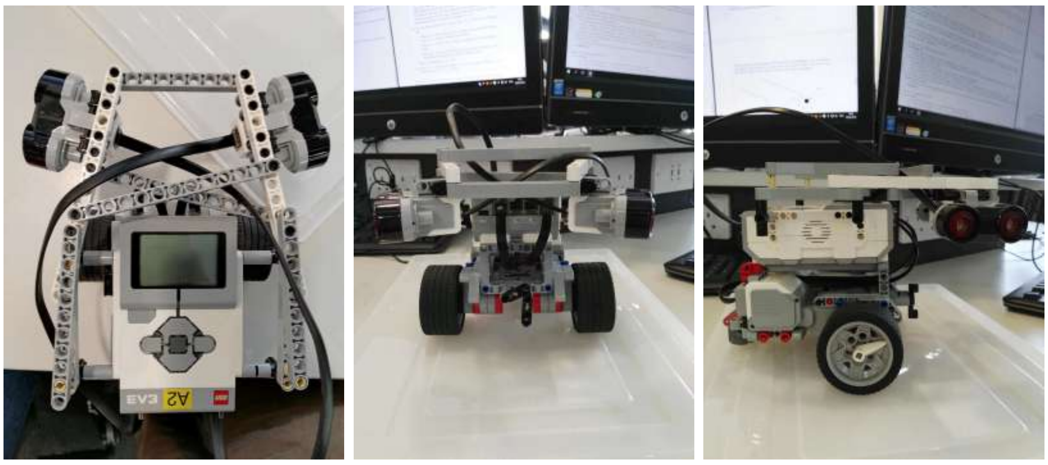


Figure 8: Final configuration of robot

The sensors were placed as wide apart as the left and right wheel of the robot, to ensure the most accurate reading of the walls without making the robot a larger object to manoeuvre. Also as shown in **Figure 8**, the sensors were aligned horizontally and not vertically. This was to maximise the cone of vision of the sensors, as they are more effective in this orientation, and to avoid accidentally sensing over the walls.

As shown below the angle of the sensors was set slightly forwards, to give it a greater viewing range, and at the same time allowing it to pick up on the positions of the upcoming walls more accurately. They were also placed below the supporting horizontal bars to ensure that they did not accidentally see over the walls.

Crossbars were added in order to give more stability to the sensors on the robot, as well as extra bracing horizontal bars to prevent the sensors making it too front heavy

Question 16: *Are there any points you wish to make about your robot's performance in the competition? For example, if you had had more time, what might you have done differently?* (Worth up to 5 marks)

During the competition, our robot hit the wall once and had to be rescued, but this was curiously during the first straight. Due to the fact that it then went to complete all of the rest of the track perfectly, including the challenging corners, we have to surmise that this was not the fault of the robot itself. We believe that it may be down to the walls of the maze being comprised of slats of wood, joined together with hinges, and that the sensor may have seen through one of the gaps, causing the robot to continue on its path towards the opposite wall instead of correcting.

One of our robot's weaknesses is taking wide turns in the maze. The position of the sensors does not scale well, so our robot always took the outside line around a wide turn. Changing this so it follows the inner wall of the turn would reduce the time taken by our robot to make the turn hence improving our overall competition time.

Another weakness is that our robot will always try to maintain a equal distance between the left wall and right wall. This causes the robot to keep turning left and turning right even though it is following a straight wall, resulting in a slower completion time compared to those which followed the wall smoothly.

Given more time, we would also have experimented more with the values in-putted into our PID controller, to find values of K_P, K_I and K_D that would best improve the quality control of the controller, making it navigate through the maze quicker without colliding with any walls. We would also implement the robot in a way such that it does not always maintain an equal distance between the left and right wall, but it only adjusts itself when it is too close to the wall. This would have made the robot movement much smoother.

Finally, how did you organise your team? I.e. what was each member's role and responsibilities, and what was each person's contribution as a %? Please fill in the Table below:

Team Member	**Role**	%
Catalin Mares	Research, report	21
David Coelho	System design, report	21
Huzaifa Ahmed	Research, report	16
Joseph Slade	Physical design, report	21
Zer Jun Eng	Coding, research, report	21