An Investigation into Pololu 3Pi+ Leader Following Robotic System Using Bump IR Sensor

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Abstract—**The goal of this research was to look into the Leader-Follower motion control of robotic systems. Leader-Follower is a system in which two bots communicate with each other in our case using an IR sensor and it allows one robot to maintain a specific distance away from a moving robot. We will get an idea by investigating how the bumper IR sensor of the Pololu 3pi+ can be used for a leader-follower robotic system. The motion control system can be used to simulate swarm robots in various environments (for example, warehouses). We proposed a raw solution to process the data from the bump IR sensor and smooth it out using an averaging filter and a PID controller to maintain a specified distance and angle between the leader and a follower. The performance was evaluated by analysing how well the robot compensates for the error to maintain the distance and angle from the leader. The system performed well enough when the follower robot followed the leader in a straight line trajectory with the disadvantage of following the leader robot in a sharp curve trajectory. In order to support our findings, additional research is suggested into how well the system generalizes and how to follow sharp curves.**

I. Introduction

The leader-follower is a two robots robotic system which is an autonomous system in which the follower robot follows the leader bot and cooperates with each other to complete a task. With an effective control system, the system can respond to uncertainties in the environment effectively like changes in ground surface, ambient light or robot hardware malfunction. This report focuses on analysing the uncertainties that might occur in the environment, which may affect the control system of the leader-follower robotic system. The control system will be analysed based on the leader robot's speed, rotation angle, and distance between the leader and the follower robot as shown in figure 1. The system should be able to navigate the environment while maintaining a rigid formation. The main challenge would be stabilising the control system and enabling it to sense the IR communication link between the two robots and overcome any uncertainty.

The follower robot must be located and rotated to the leader robot. It should be able to track the leader's progress. We experimented with two Pololu 3Pi+ 32U4 boards that lacked basic communication hardware. In order to ensure that the leader can be tracked by the follower, the front-facing bump IR sensors were used as part of the mechanism, in which the leader emits IR through its IR LEDs, and the follower receives IR through its IR receivers. A bump infrared sensor is an active sensor that transmits a signal and measures the response that it receives in return. When the distance or angle of the leader robot changes, the IR value changes.

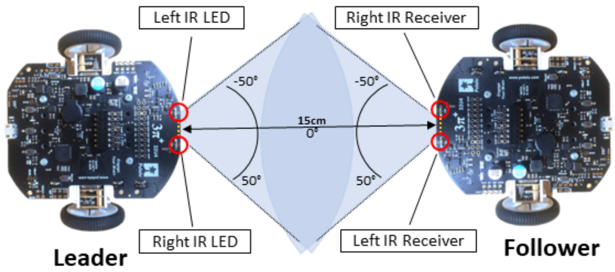

Fig. 1. The figure depicts the sensor positioning and the ideal distance and rotation range between the leader and the follower

A. Aims and Objectives

We aimed to develop a motion control system which can be used in a leader-follower robotic system. This system can be utilized in warehouse robotics where one robot will be the leader and the other robot will be the follower which will track the leader's trajectory.

Our first objective was to analyze the conditions where the follower robot will fail to follow the leader's path. The proposed system consists of two PID controllers for the follower robot in order to compensate for distance and angle errors as compared to the leader robot. As a result, we are using the distance and defining some upper and lower thresholds for the IR value for a specified distance, and using the values as an input to the PID controller, which attempts to reduce the error caused by external forces by independently actuating the left and right wheels of the follower. If the method is correctly implemented, the follower robot should be able to follow the leader in a straight trajectory for a specified speed without losing IR contact with the leader.

The following is how the report is organised: Section II describes the hardware and software features used in the analysis, as well as some presumptive values specified for developing a stable leader-follower control system based on the proposed PID controller. Section III depicts the various methods of experimentation that were used to formulate our hypothesis. Section IV presents the experimental results as concrete evidence for our hypothesis. Section V and Section VI compiles the final results and discusses future work that can be done to improve the control system in terms of hardware and software.

B. Hypothesis Statement

After the characterisation of the bump sensor, the following hypothesis places an emphasis on maintaining a specified distance and angle between two robotic systems (i.e. Pololu 3Pi+). We expect that,

Hypothesis 1: *"It is possible to get both the robots to follow one another using IR sensors at low speeds and for small angular changes"*

Hypothesis 2: *"The follower bot will fail to follow the leader bot at high speeds even after calibrating the bump IR sensors to have the same level of sensitivity and adding PID controllers on the sensor readings and wheel speeds of the follower."*

II. Implementation

A. Bump IR Sensor

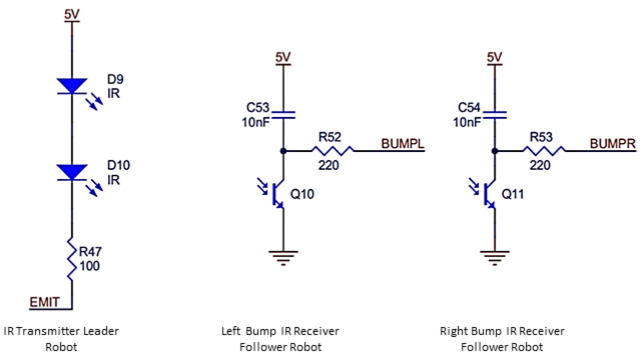

Fig. 2. Bump IR schematic for Pololu 3Pi+ (Image credit: Paul O'Dowd) [1] [2]

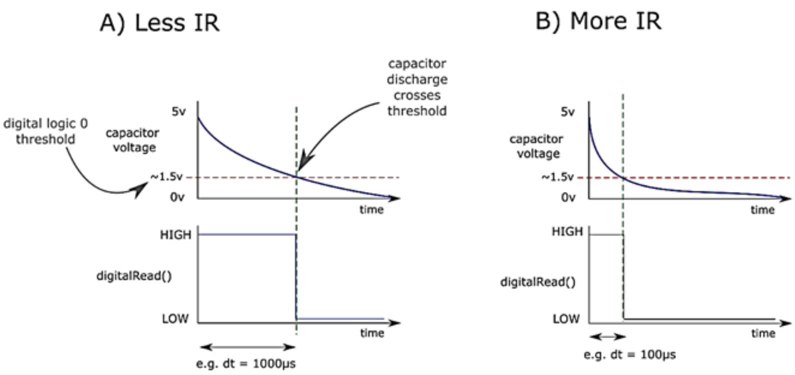

Fig. 3. Bump IR reading for Pololu 3Pi+ (Image credit: Paul O'Dowd) [1]

For Pololu 3Pi+ we read the bump IR sensor data by reading the charge and discharge of a capacitor as shown in the schematic Figure.7 and Figure.2 [1]. The detecting circuits utilise a photo-transistor in a small electronic circuit to control the rate of charging and discharging of a capacitor. Varying the IR light on the photo-transistor will change the time it takes for the capacitor to discharge [3]. As for the IR reading, we are measuring how long it takes for the capacitor to discharge.

1) Moving Average Filter
The bump IR sensors were highly sensitive so the data from the sensor were noisy. The moving average filtering method, which smoothes the noisy data from the signal, was used to filter out the noise. It is a streamlined version of a low-pass filter. Figure 4 shows the IR readings with and without the filter.

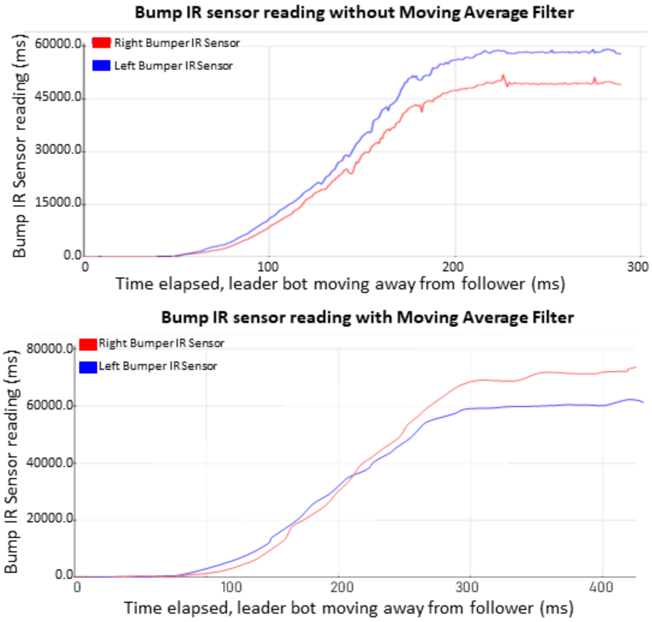

Fig. 4. Bump IR sensor reading with and without filter

In the filtered reading, the noise has been removed leading to a smoother reading as one robot moves away from the other [4]. For our requirement, 10 samples were taken from the IR sensor and the output was averaged to remove the high-frequency noisy data. The block diagram for the moving average filter used is shown in Figure.4:

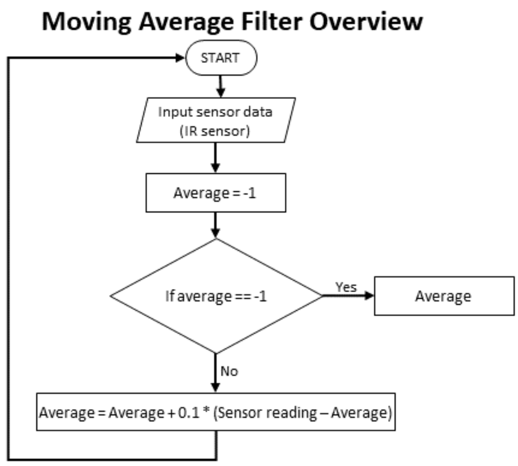

Fig. 5. Moving Average Filter architecture

The bump IR sensor function operates between the maximum and minimum settings as shown in figure6. The function's slope is proportional to the strength of the IR signal from the leader robot, which is determined by the distance between the leader and the follower. As a result, we are using the distance and defining some upper and lower thresholds for the IR value for a specified distance, and using the values as input to the PID controller.
As figure 6 illustrates the useful region and the ambient light region of the IR sensing function. We designed the proposed controller with a lower

threshold of 150 and an upper threshold of 6000 IR sensor range which is mapped between -1 to 1 as shown in figure 7. The value is fed to the PID controller after mapping, which maintains the distance between the leader and the follower.

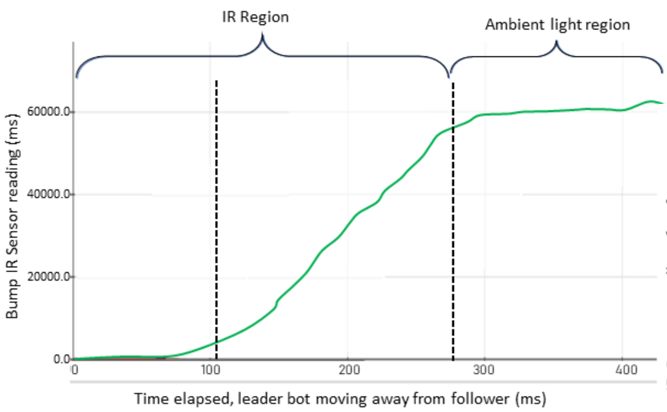

Fig. 6. IR function generated by changing the leader-follower distance

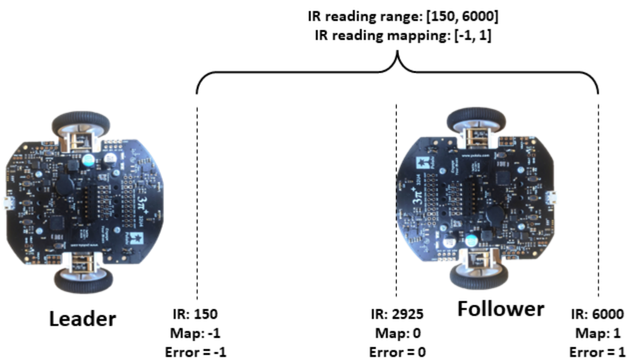

Fig. 7. Representation of the IR reading range that is used to maintain the distance between the leader and the follower

2) Characterisation of IR sensors

- Characterisation Methodology
  - ***Experiment 1***

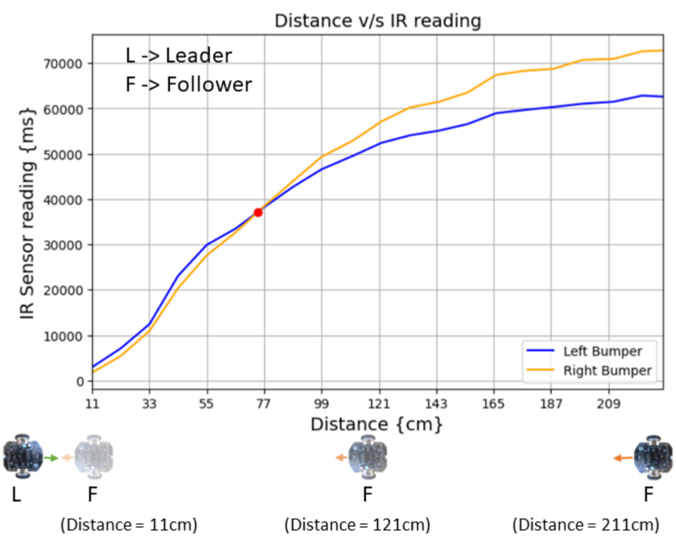

Fig. 8. Follower bot kept constant, leader bot moving away from follower ranging from 11cm to 211cm

Figure 8 shows how the IR sensor reading increases in a non-linear way with an increase in distance. The leader robot's displacement measurements were taken by hand based on the point marked by the gap between the bumper sensors, while the follower robot's displacement measurements were constant.

- ***Experiment 2***

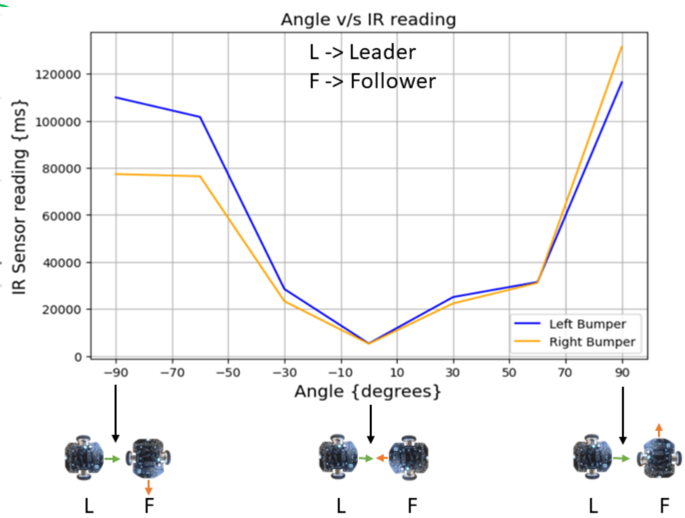

Fig. 9. Leader bot kept constant, follower bot rotating w.r.t.leader bot ranging from -90° to 90° where 0° is face to face

Figure 9 shows how the IR sensor reading increases at the boundary which ranges from -50° to 50° and gradually decreases following a parabolic curve. The distance between the leader and follower bot remains constant, at 15cm, while the angle of the follower bot changes.

B. PID control for leader follower

1) PID (Leader)

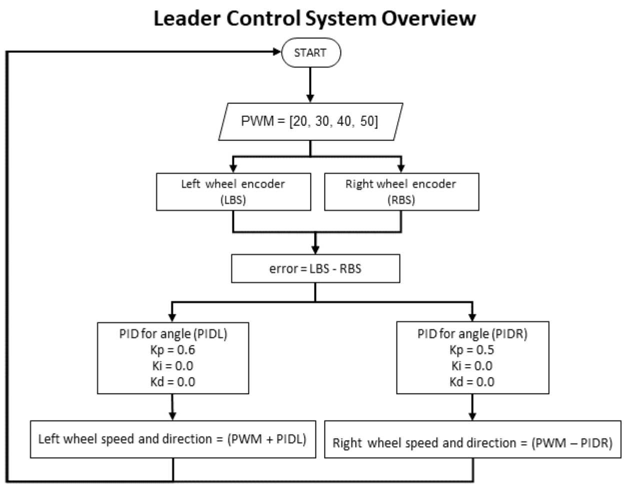

Fig. 10. Leader robot software architecture

The robot does not move in a straight line and tends to drift to the right due to manufacturing flaws. The leader robot was outfitted with a proportional controller to deal with this situation. Figure 10 illustrates the architecture of the proportional controller added to the leader robot. PWM values are set, and the values of the wheel encoder are read. In this case, the demand was set to zero as it was desired to have the leader move in a straight trajectory which was achieved when the wheel encoders have the same values. The proportional controller is therefore trying to minimize the error between both the wheel encoders.

2) PID (Follower)

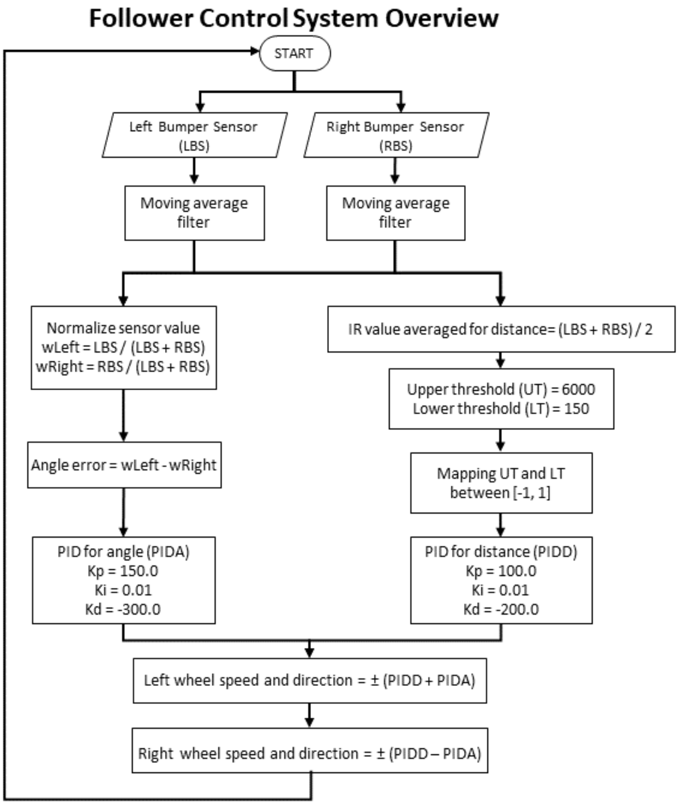

Fig. 11. Follower robot software architecture

Figure.11 illustrates the proposed software architecture in which the PID controller was used for adjusting the speed and directions on the wheel to reduce the distance and angle error between the follower and the leader.

One PID is implemented to evaluate the difference between the two bump sensors where the demand value is set to zero for the follower bot to correct the angle in accordance with the leader bot. An angle difference causes the follower bot to rotate clockwise or counterclockwise with respect to the leader bot that returns the difference to zero.

The second PID is implemented to evaluate the difference between the distance between the two robotic systems where the demand is also set to zero for the follower bot to correct the distance error with the leader bot. A change in distance between the follower and the leader bot, the follower bot moves forward or backwards with respect to the leader robot that returns the distance error to zero.

III. EXPERIMENT METHODOLOGY

A. Overview of Method

The experiments were carried out with two Pololu 3Pi+ robots, one as a follower and the other as a leader. The analysis was performed using the distance between the robots, the angle between the robots, and varying the leader's speed. For each angle and distance, five trials were recorded in experiments 1 and 2. For experiment 3, 200 data points were collected over 20 seconds at various speeds.

B. Discussion of Variables

- **Controlled Variables**:
  - Task: The initial distance and rotation between the two robots are kept constant so that the experiment can be carried out with minimal deviation. A tape marker was used to reposition the robots to their initial position.
  - Hardware: As part of our experiment, we used two identical robots (Pololu 3Pi+) to reduce the uncertainties in our analysis that could affect the measurements. One bot was designated as the leader, while the other was designated as the follower.
  - Software: The leader's left and right wheels were controlled independently by the proportional controller, and the PWM values were set as follows: (20,30,40,50). To ensure consistency, the same PID coefficients were used throughout the experiments.
  - Environment: For all trials, a smooth wooden desk is used to ensure a constant friction coefficient affecting the wheels throughout the experiments, ensuring consistency in the results. To prevent non-uniform IR readings, the same environment was used with no exposure to sunlight and a common effect of ambient lights.
- **Independent Variable**: The implementation of two PID controllers to control the follower's wheel speed to maintain the distance and angle with the leader and one proportional controller to control the leader's wheel speed to travel in a straight trajectory is the independent variable in the proposed control system scenario.
- **Dependent Variable(s)**: The ability of a follower bot to follow a leader bot is investigated in this study using a bump IR sensor. As a dependent variable, capacitor-discharge rates were used to read the IR values from the follower robot.

C. Discussion of Metric(s)

The mean values for each data point in our experimental scenario were observed for evaluation. For experiment 1, 5 samples were taken for each distance ranging from 11 to 211, and the mean was calculated for those five samples. Figure 10 depicts the distribution of experiment 1. Similarly, 5 samples were taken for each angle ranging from -90 to 90 at a distance of 15cm between the leader and the follower in experiment 2, and the representation is shown in figure 11. We used the mean values for our analysis because outliers may occur when the follower bot loses communication with the leader bot and begins reading ambient light readings, which will affect the representation, and because the values from the bump IR sensor were in a similar range, using the mean was more logical as metrics for analysis.

IV. Results

Experiment 1 shows that the IR reading increases with increasing distance. Because of the different sensitivity of the sensors, the readings from the left and right bump IR sensors differ slightly. *The IR values gradually increase from 3cm (the minimum distance for the IR sensor to read the IR LED data) to 11cm. The IR reading increases dramatically from 22cm to 166cm; after 166cm, the reading becomes constant.* For our analysis, we kept the follower robot at a 20cm distance from the leader. We restricted the follower robot's range to 3cm and 30cm. To reduce outlier data points, we assumed the follower robot lost the IR signal from the leader robot if it moved beyond 30cm. Even though the IR signal can be sensed up to 166cm, the angle also impacted the follower robot's performance. As a result, we discovered an increase in distance error and inconsistency.

Experiment 2 shows the results of the angle deviation between the follower bot and the leader bot can be calculated using Figure 9. The follower bot can follow the leader for an angle deviation ranging from -50° to 50° with a distance of 15cm between them. If the angle exceeds -50° and 50°, the follower bot reads ambient light values from the bump IR sensor, indicating that it has lost communication with the leader bot and is unable to follow it.

V. Discussion

The bump IR causes the follower robot's rotation and speeds to synchronise with the leader robot's trajectory. The proposed PID controller performs reasonably well in keeping the follower robot's specified distance and rotation angle with respect to the leader robot. However, as we predicted, the follower robot fails to keep up with the leader robot's high speed. The results are convincing because the robot is expected to operate in this manner due to hardware constraints. Despite its limitations, the robotic system developed using two Pololu 3Pi+ robots demonstrated autonomy.

However, there is still room for improvement in our system. The problem in our experiment was the follower robot's constant jerking. The movement could have been smoother, causing rapid back-and-forth movement in the follower robot's left and right wheels. We should focus on reducing jerking behaviour to compensate for the error and maintain a smooth trajectory with the leader robot.

Figure 12 illustrates that the leader robot travels backwards in a straight line at a set speed. The speed was set using PWM values in the leader robot. The PWM values range from 0-255, but the robot's motors have a dead band, which means that PWM values ranging from 0-15 do not move the motors. As a result, the trial was conducted for PWM = [20, 30, 40, 50]. After 100ms had passed since the start of the code for 20 seconds, 200 samples were collected for each PWM value. The error value in the IR reading was recorded, which ranges from -1 to 1 since the values are normalised.

VI. Conclusion

Referring to the figure 12 we can infer that for PWM values 20, 30 and 40 the leader-follower robotic system performed well with the proposed control system and from the figure (angle) the robotic system was able to navigate slight curves. Whereas, for a PWM value of more than 50 the proposed motion control system fails as the error produced increases exponentially. It is found that the preliminary experiments performed yield significant results that allow us to conclude that *"It is possible to get both the robots to follow one another using IR sensors at low speeds and for small angular changes as shown in figure 13 and when the leader is moving at a high speed, the follower fails to maintain the specified distance."*, as we hypothesised.

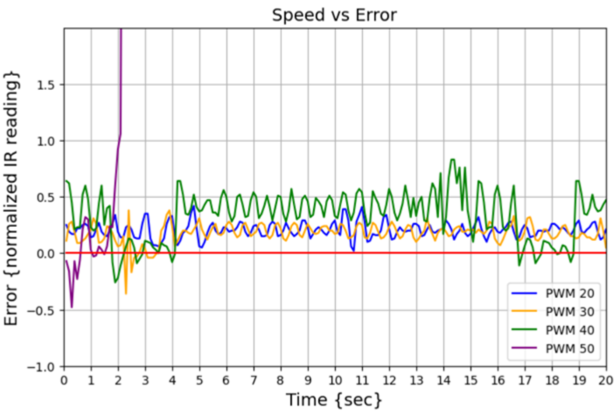

Fig. 12. Follower bot following Leader bot with varying PWM values to get the plot between PWM vs IR distance error from PID controller

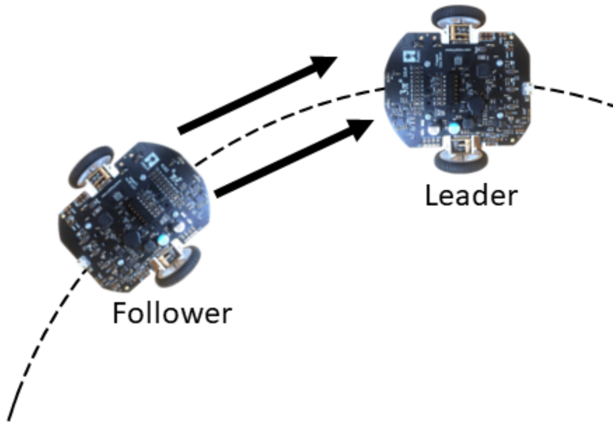

Fig. 13. Leader-Follower motion control on a long curved trajectory

A. Limitations and Future Work

There are several significant limitations as a result of our research. We only tested our system on a straight line, and no attempt was made to analyse the robotic system's performance for different trajectories involving slopes, variable surface types, or sharp bends as shown in figure 14, and under different lighting conditions (outdoor lighting) which are common in real-world control systems. If our system fails under its current implementation, we can investigate the next logical step by better understanding how it works under our experimental conditions. To improve the performance of the robotic system, the PID parameters can

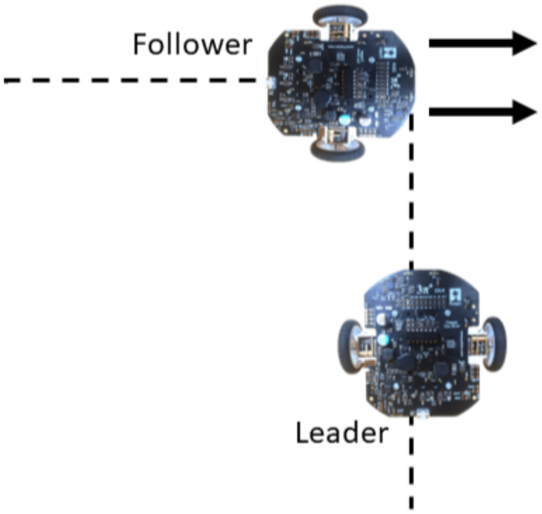

Fig. 14. Leader-Follower motion control on a sharply curved trajectory

be tuned using various optimisation methods because PID parameters can be time-consuming and resource-intensive to tune manually. We propose quantifying the smoothness of the PID control response if we have more time to research this system.

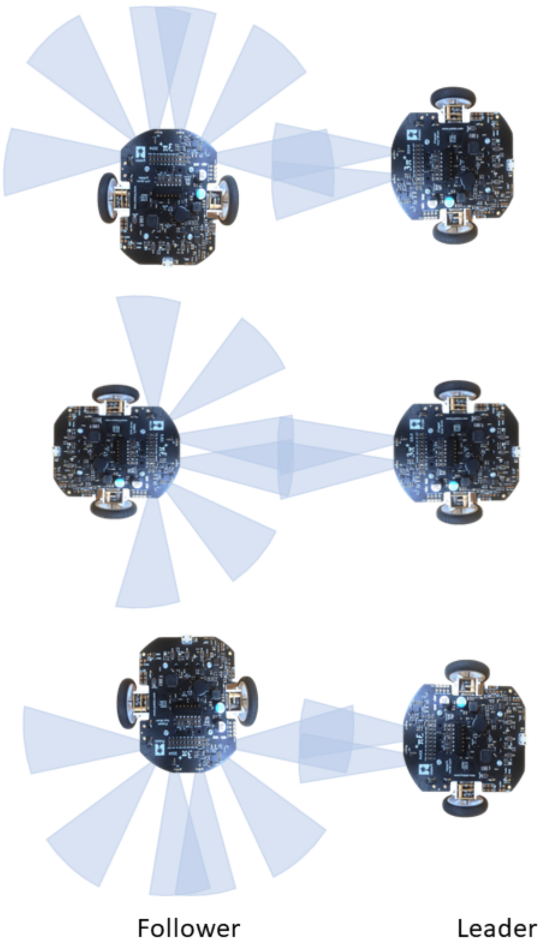

Fig. 15. Adding more IR sensors to the follower robot

Figure.15 illustrates how we can reduce the robotic system's blind spots. Future research should consider how performance changes by adding more IR sensors at different angles to the follower robot rather than front-facing. The follower robot will have improved manoeuvrability and can follow sharp curve trajectories. More optimised filters should be used to smooth the signal, affecting the follower's wheel speed against jerking without compromising its ability to respond to leader behaviour.

References

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