Leader-Follower Formation using Bump Sensors in Pololu 3pi+ robot

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Abstract— Multi-robot systems have the capacity to resolve task complications, and increase performance, and dependability by undertaking collective behaviour that would be impossible for a single robot to achieve. In this paper, we assess the sensitivity of bump sensors in a Pololu 3pi+ robot for designing and controlling a leader-follower configuration. First, a model for leader-follower robot formation based on PID controller readings between the robots is developed. An improved control method was subsequently devised by using a low pass filter and incorporating turning into the PID controller. The accuracy of this system was tested using the leader-following challenge and two metrics were used for each iteration of the leader-follower challenge to evaluate the precision of leader-following behaviour. Our leader-follower system performed well while following a straight line and curve trajectories, with the drawback of not being able to follow very acute angles. Experimental data have shown the effectiveness of the leader-follower method, and future work to improve the system has been proposed.

I. Introduction

A robotic system can solve a set of problems by combining strength, accuracy, repeatability, and the ability to withstand harsh conditions. Developing a multi-robot system (MRS) instead of a single robotic system has been a major focus of research because of its numerous potential benefits such as increased spatial diversity, overall system completion, reliability, and variable placement [1]. Designing an efficient control architecture with a strategy for robot coordination that enables them to execute increasingly complex behaviour is the biggest challenge. Coordination is essential to the MRS's effectiveness because poor coordination can affect the system's performance and quality. One of the key studies in this field is the leader-follower concepts and variations of this strategy. The position and task of the follower robot in this technique are determined by the position of the leader [2]. We analyse these problems using a leader-follower control approach, in which the leader follows a path, and the follower maintains a specified position to the leader. The Pololu 3pi+ is used for this experiment, which uses its bump sensors without its plastic shell to transmit and receive IR data required for establishing a leader-follower system. The IR LED of the bumper sensors on the leader robot emits IR radiation which is measured by the IR receiver of the follower robot. The follower robot moves and turns in response to these values which are the time it takes for the capacitors of the left and right bump sensors to discharge in microseconds. As a result, this research studies the use of bump sensors to achieve a leader-follower system.

A. *Aim:* The aim of this experiment is to investigate the application of the bump sensors of the Pololu 3pi+ robot for implementing Leader-Follower behaviour.

B. *Objectives:*

- Establish Communication between the robots, the leader emitting IR and the follower receiving the IR.
- To design a Leader-follower system using Pololu 3pi+ robots.
- Implement moving forward using the communication established and using PID to maintain a constant distance between the leader and follower robots.
- To determine the limits in distance and orientation at which the follower robot can still communicate with the leader robot.
- To determine how precise and accurately the follower robot follows the leader robot along curves and angles.

The rest of this paper is structured as follows: Section C describes the hypothesis; Section 2 presents the implementation; Section 3 presents the methodology undertaken step by step to achieve the aim; Section 4 provides the results obtained from this project and finally section 5 discusses the data obtained, future work and the conclusions drawn from this paper.

C. Hypothesis Statement

We hypothesise that once leader-follower communication is established successfully using bump sensors, it can:

i) The follower robot should be able to remain in communication with the leader robot until it goes out of range.
ii) Leader following performance is more consistent in a straight line than while turning or following curves.
iii) The follower robot is able to maintain a specific distance from the leader robot, during a range of different manoeuvres.
iv) The data collected by the infrared sensors is noisy and applying a filter to the sensor readings will improve follower performance.

The hypotheses are investigated through a series of organised experiments performed on the Pololu 3Pi+ mobile robot, evaluating the performance of the bump sensors with and without the use of a filter. The purpose of this research is to determine if the reflectance bump sensors on the 3pi+ offer sufficient data to maintain an accurate leader-follower system. The studies were conducted using a Pololu 3pi+ without its plastic shell to reduce obstruction between the readings of the leader and follower (Figure 6).

II. IMPLEMENTATION

Experimental setup conditions: We performed the experiment in a light-controlled room to reduce ambient light. When testing leader-follower behaviour, the leader and the follower robots are initially placed approximately 4 cm away from each other to avoid any chaotic responses when the robots are too close. For example, when the robots are placed too close to each other, there is a spike in the readings as shown in the graph illustrated in figure 2.

Pin configurations: For the leader-follower behaviour, the two bump sensors must face each other when emitting and receiving as shown in figure 6, hence based on the Pololu schematics the leader has to move in reverse.

Two bump sensors facing forward are present on the 3pi+ robot. The two bump sensors, like the line sensors, are reflectance sensors, but they can also measure any change in reflected light off the two plastic bumpers present in front of the 3pi+ robot. This allows the 3pi+ to determine when and from which side it has come into contact with another object. On the control board, the right and left bump sensors are labelled as BR and BL, respectively.

The same pin, marked as EMIT, controls the infrared emitters for the line and bump sensors. When this pin is low, the infrared LEDs on the bump sensors are illuminated. On the follower robot, the IR LEDs of both bump and ground sensors are turned off by setting the EMIT pin to INPUT so it will not obscure our reading from the leader. The EMIT pin was configured for OUTPUT and set to LOW for the leader robot and INPUT for the follower robot to enable communication and create a leader-follower behaviour.

The reflected ambient light significantly affects the bump sensors as they detect variations in IR light intensity. Hence we performed our experiments in a room where the lighting was controlled. We use a PID controller to modify the follower's behaviour in response to the leader's readings.

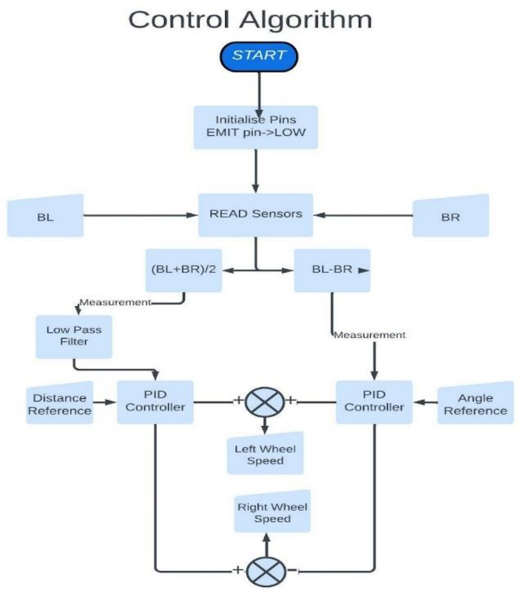

Figure 1: Control system for Follower-robot.

Sensor readings and PID control: It was necessary for the follower robot to be able to communicate with the leader by receiving the IR readings. A signal response (as shown in section 4i, Fig 2) of the bump sensor signals were graphed to determine the ideal distance from which the follower robot may precisely follow the leader by aligning the leader directly in front of the follower. The average of the sensor reading was calculated to reduce systematic errors such as bias. We use a PID controller for both wheels, along with average values of readings obtained from the left and right IR sensors of the leader robot, to implement the follower robot moving forward and maintaining an ideal distance. However, when the follower robot reaches its set distance from the leader, it stops abruptly causing a change in the follower robot's alignment with respect to the leader. To reduce this, using a low-pass filter was investigated. The filter was applied to the input of the PID controller. As the follower follows the leader in a straight line, it tends to drift away from the leader's path and loses communication with the leader robot.

The next experiment (further/results described in Section 4(ii)) aimed to address this drifting behaviour to make the follower robot more consistent and examined how the orientation between the follower and the leader influences the difference in the two IR sensor measurements of the follower robot (see Figure 4). To maintain communication with the leader, we correct the orientation of the follower with a PID controller (Figure 1) and hence produce a stable following behaviour.

III. EXPERIMENT METHODOLOGY

The experiments evaluate the sensitivity of bump sensors in order to accurately build a leader-follower system. Three distinct scenarios were evaluated and compared - i) Moving straight ii) turning iii) Leader-following challenge.

A. Overview of Method

i. Moving straight: To determine the ideal distance from which the follower robot can precisely follow the leader, a thorough analysis of the bump sensor readings was conducted. In the first experiment, the follower is positioned directly in front of the leader, and bump sensor readings are recorded by placing the follower robot at distances starting at 0.5 cm in increments of 0.5 cm. After the follower robot is positioned at a set distance from the leader robot, the follower took 50 measurements for both left and right sensors, from which the mean was calculated. Figure 2 depicts the distribution of average sensor readings plotted against the distance from the sensors. Values were measured at 14 distinct intervals, through a range of 0.5 cm to 7 cm. At a distance of 3 cm, the minimum error between the left and right bump sensors was attained. As a result, this was chosen as the ideal distance between leader and follower.

To implement moving straight, we use a PID controller to control both wheels which uses the average values of readings collected from the leader robot's left and right IR sensors. The amount of time the follower robot could maintain communication with the leader robot was measured. 15 trials were performed to compare the communication time

(Figure 3) and measure the performance of the leader following behaviour with and without a low pass filter.

A comparison of communication time (Figure 3) was performed over 15 trials to evaluate the performance of the leader following behaviour with and without a low pass filter.

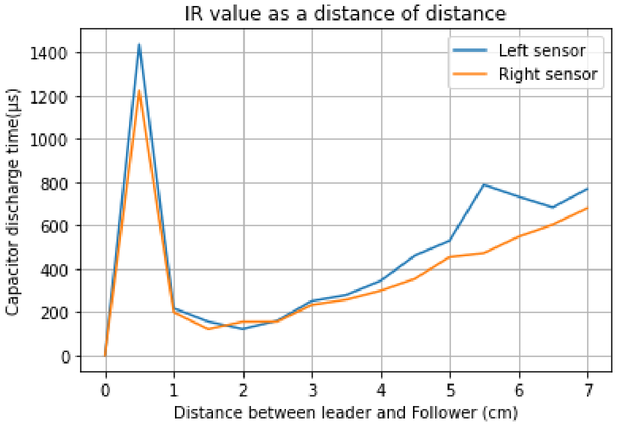

Figure 2: IR value as a function of distance.

Results: Figure 2 illustrates the IR sensor response of the Follower robot (i.e capacitor discharge time) with respect to the distance between the IR emitter of the Leader and the IR receiver. From the graph, after the initial spike, we have a linear response for the discharge time.
An arbitrary point can be chosen between 2 cm and 7cm for a set point. These responses are usually part of an s-curve function so the set distance should not be too wide. We chose 3 cm for our set distance. When setting up for our experiments, the robots were placed at least 4 cm away from each other to avoid uncertain responses at a closer distance.

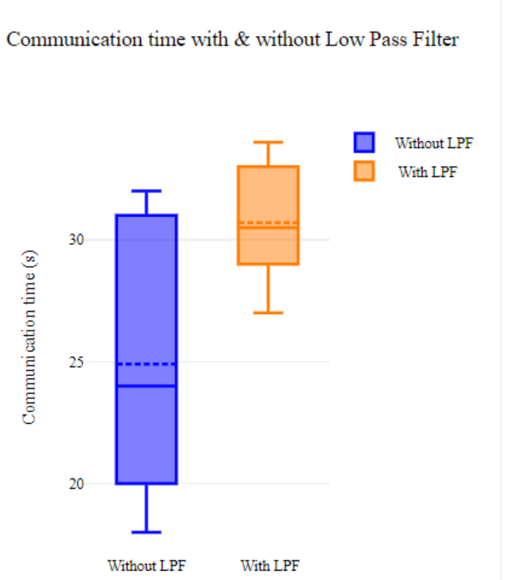

Figure 3: Comparison of leader-follower communication time with and without Low Pass Filter (LPF)

After implementing our PID controller using average values obtained from readings, we tested how long the follower could maintain communication with the leader with and without the low pass filter on the feedback to the PID controller. The results of this comparison as shown in Figure 3 show a wide variation in communication when the robot has no filter. Without the low pass filter, the follower robot stops abruptly when it reaches the set distance from the leader robot, this leads to slight changes in orientation. The filter reduces the jerky motion of the follower robot leading to a more stable motion and longer communication time.

ii. Implementing turning:
To attain steady following behaviour, this experiment examined how the angle at which the follower collides with the leader affects the bump sensor values. For this experiment, the follower is positioned 2.5 cm from the leader with angles ranging from -80 to 80. From its initial point, the follower took 50 measurements for both left and right sensors, from which the mean was calculated. The measurements obtained for each angle from the sensors are shown as a line graph in Figure 4.

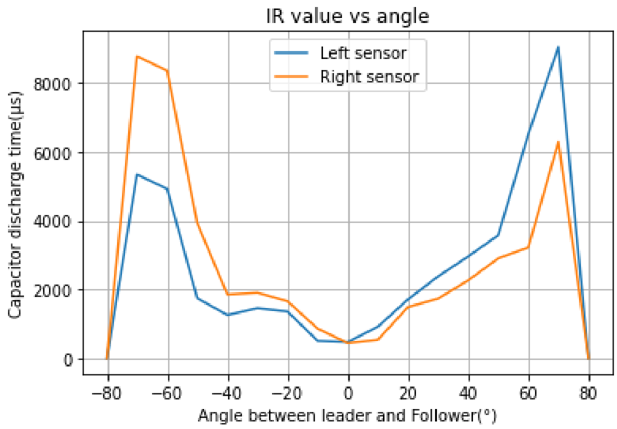

Figure 4: IR sensor readings against difference in orientation

Results: To accommodate for the drift between the leader and the follower, we needed to get the response of the IR sensor with respect to the difference in orientation (figure 4). Figure 5 shows us the difference between the left and right IR sensors, and we can observe that leader-following communication is disrupted when the robots are misaligned by more than 40 degrees.

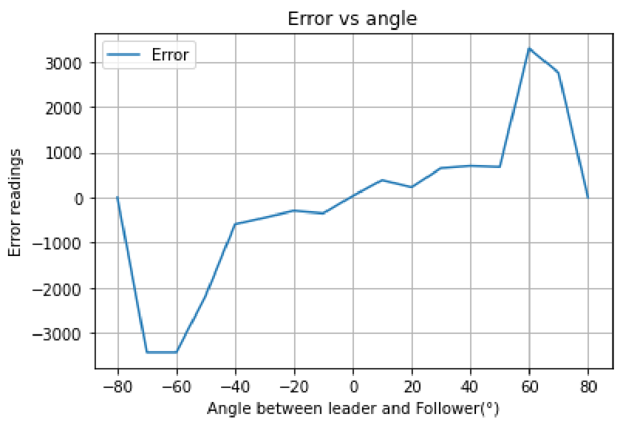

Figure 5: Difference in sensor readings against difference in orientation.

The error in Figure 5 is used with a PID controller to rotate the robot slightly and realign with the leader robot. The Follower robot did not lose the leader and maintained communications after another PID controller was introduced to account for the change in orientation, only losing confidence in rapid and acute turns exceeding 40 degrees.

iii. Leader-following challenge:

To check the accuracy of leader-following behaviour, the results obtained from the above experiments were used in completing the leader-following challenge. The leader was programmed to accelerate and decelerate in a straight line and rotate at acute angles of 30°, and 40° as well as complete larger turns of 90° and 180°. To keep track of how well the follower robot follows the leader robot's trajectory, highlighters were attached to the robots as shown in figure 6. For the test, the distance between the highlighters attached to the leader and follower robot was set to 25 cm. The highlighter draws the path in which the robots move and shows that the leader-follower challenge was successfully completed. This experiment was repeated 20 times to check the accuracy of the following behaviour by measuring the maximum deviation obtained from the track of the follower from the leader and the distance between the highlighters at the end of the leader-following course.

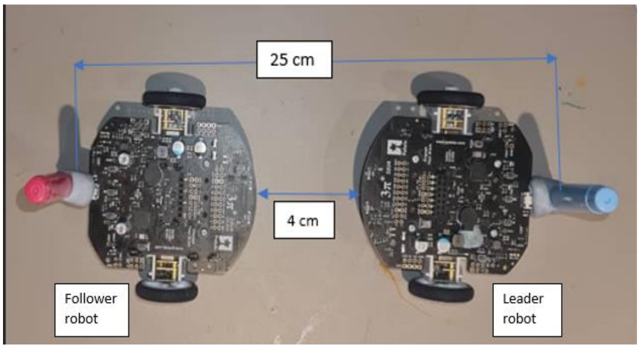

Figure 6: Highlighter attached to robots

A. *Discussion of Variables*

i. Controlled variables:

- **Environment:** The experiments were carried out in a room with controlled lighting due to the sensitivity of bump sensors.
- **Hardware:** Due to possible variations in the sensor readings, the leader-follower role was assigned to the same robot throughout the experiment.
- **Software:** The route of the leader robot is programmed for each experiment.

ii. Independent variables:

- **Route:** The robot is controlled to either move in a straight line, rotate, or make a corner or U-turn
- **Leader Robot Velocity:** The speed of the leader robot is constant for the first experiment but is varied in the leader-follower challenge.
- **PID controller gains:** The values of the proportional, integral and derivative gains to control the follower robot's behaviour were adjusted.
- **Set distance:** This is the desired distance from the leader robot that we intend the follower robot to maintain.
- **Filter:** A low pass filter to reduce the noise of the response.

iii. Dependent variables:

- **Measured distance:** This is the resulting distance maintained as the follower robot follows the leader robot.
- **Follower Robot Velocity:** The speed and direction of the follower robot's motion are a result of the speed and orientation of the leader robot's motion.
- **Communication Time:** This is the amount of time the follower robot can maintain communication with the leader robot.
- **Deviation:** This is the distance between the path of the leader and the path of the follower at any point in the course.

B. *Discussion of Metrics*

To measure the accuracy of leader-following behaviour, these two metrics were taken for each iteration of the leader-follower challenge:

- **Maximum deviation:** To measure how accurately the follower aligns with the leader's path, the maximum distance between the two tracks of the leader and follower was calculated. We compare the differences for straight-line, angular, and curved motions. We calculate the average of this distance for all the iterations of the experiment. This method is limited by not taking the deviation at different points through the path. The advantage of finding the maximum deviation is that it illustrates how a sequence in the leader's operation affects the efficiency of the follower's behaviour.

- **Absolute Error:** The snapshot of the difference in position between the leader and follower robots at the start and end positions is measured. This approach has the disadvantage of not taking continuous measurements at consistent timesteps. To determine how successfully the leader and follower keep their distance throughout the course we calculate the mean absolute error. The error is useful in understanding how precise the follower maintains the distance from the leader robot.

$$\delta = \left| \frac{v_A - v_E}{v_E} \right| \cdot 100\%$$

δ	=	Absolute error (%)
v_A	=	Final distance (cm)
v_E	=	Initial distance(cm)

IV. RESULTS

The leader-follower challenge was designed to evaluate the accuracy and precision of the leader-follower system. To assess the overall performance of the system, two benchmarks were measured over 20 trials: maximum deviation and mean absolute error.

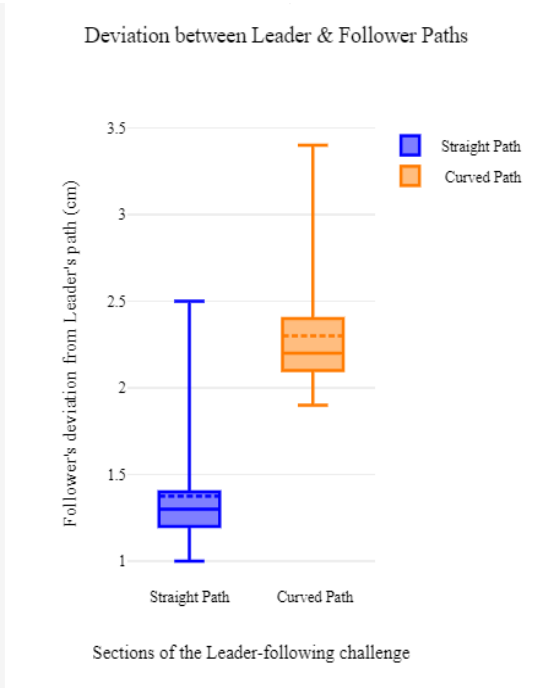

Figure 7: Illustration of deviation along Leader-Following challenge

1. **Maximum deviation**: The maximum deviations of the challenge trials are shown in Figure 7. We consider this metric for 3 sections of the course:
    a. **Acceleration and deceleration along a straight line:** The follower does not deviate more than 2.5 cm across all the experiments with an average deviation of 1.4 cm. The follower was also able to maintain a steady path as the robot varied its speed. The deviations were all on one side of the path, this can be due to a bias error in the system
    b. **30 and 40-degree tight angles:** From Figure 8, it can be seen that the response of the follower robot is shifted by approximately 25 cm due to the robots' initial positions. This shift made it difficult to take quantitative recordings with only qualitative inference. The deviation is more inconsistent since following sharp curves is challenging for the follower, however, the communication is not disrupted. The deviation of the 30-degree turns has higher following stability than the deviation of the 40-degree turns because it becomes more difficult to follow smoothly with an increase in change in orientation. The robot's incapability to follow tighter angles and turns is due to the position of the bump sensors on the Pololu 3pi+.
    c. **90 and 180-degree curves:** While tight angles are difficult, the follower system performs well on curved paths with only a maximum deviation of 2.3 cm and a maximum deviation of 3.4 cm across all experiments. It is expected for the deviation at the curved path would be higher due to the leader robot always changing directions, but the follower robot maintained communication with the leader robot accurately.

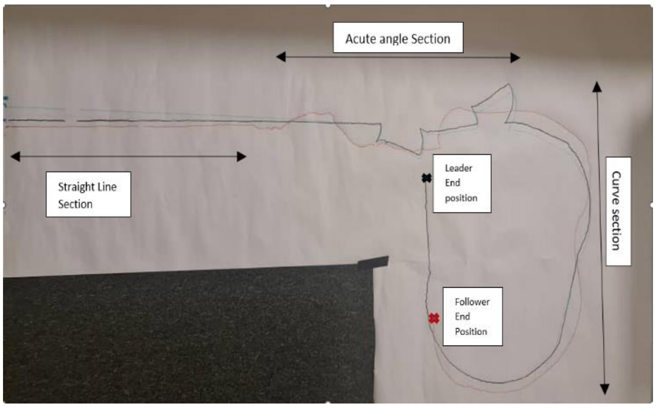

Figure 8: Path of the Leader(black) and path of the Follower(red)

2. **Absolute Error:** From the box-plot graph (Figure 9) of the error, we can see that the Mean Absolute Error is only 3.66% showing that the follower was precise in maintaining the distance from the start of the course to the end with high repeatability. It stopped between a range of -2.4% to 6.8% of the initial distance.

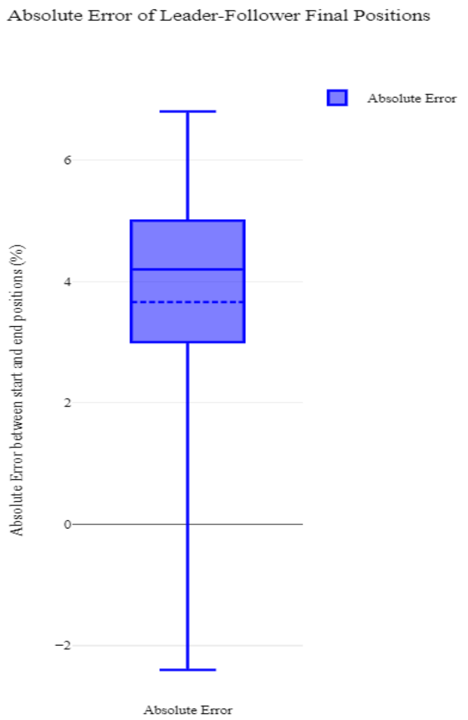

Figure 9: Absolute Error of end positions of Leader-following challenge

Based on these metrics, the leader-follower system works smoothly and accurately in most cases. The bias in our readings is due to the individual sensitivity of the IR receivers, therefore causing a systematic error.

V. Discussion & Conclusion

In terms of our hypothesis, we were successful in establishing communication between the leader and the follower and in forming a leader-follower system. Although initial applications of the bump sensors only performed leader-follower behaviour in a straight line for a short period of time, the objective was achieved. Furthermore, significant improvements were attained by applying a low pass filter before the PID controller as we predicted. The response of the IR sensor to the difference in orientation was evaluated to account for the drift between the leader and follower. This resulted in consistent leader-following behaviour, with only rapid and acute angle turns exceeding 40 degrees causing a loss of confidence. Nevertheless, by completing the leader-following challenge, our leader-follower system exhibits a high degree of confidence in its behaviour. Although there is still room for improvement, the developed leader-follower system produced less jerky motion and was capable of following the leader in a straight trajectory during acceleration and deceleration, performing complex angular turns. An analysis of the follower robot's behaviour shows the limits of communication when the robots are misaligned by over 40 degrees.

The metrics used to assess the accuracy of the leader-follower system are limited since they do not account for deviation at various points along the course. So, even if the robot followed the path correctly 95% of the time, it could end up scoring low if it has a high deviation at a single point. Figure 8 was able to provide a qualitative analysis of the system and it shows a steady following behaviour as the leader robot accelerates, decelerates, and performs multiple turns. This system can be used to reduce the computational load of a system by allowing the leader to perform the localisation, mapping, and path planning on the leader.

Future work: Currently, the leader robot does not take readings from the follower robot to establish communication. For future work, the setup implemented on the follower robot can also be implemented on the leader robot to design a more efficient leader-follower behaviour.

The leader-follower system we designed only involves one follower. For further work, another follower robot can be added to the system to create a Multi-Robot System, unfortunately, the Pololu 3pi+ does not provide enough sensors and an alternative means to be chosen.

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