IR Pulse Emissions: A Roboust Alternative to Continuous Emissions in Leader-Follower Systems

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***Abstract*—This paper investigates the communication and tracking capabilities of two Pololu 3Pi+ robots using IR pulse emissions for the leader-follower formation. The study explores the relationship between bump sensor readings and the separation between the robots, identifying optimal communication ranges (3-8 cm) and leader rotation angles (±50°). Various ON-times for IR pulses (0.1 ms to 1 ms) were tested, with 0.1 ms found to be optimal for both straight-line and turn maneuvers. The findings also highlight the impact of ambient light and pulse emission duration on the follower's ability to track the leader, and offer solutions for improving tracking robustness.**

I. Introduction

Multi-robot systems have emerged as a compelling area of research due to their ability to accomplish tasks more effectively compared to single robot systems, leveraging distributed sensing, spatial diversity, and scalability [1], [2]. Among the various coordination strategies, the leader-follower formation has gained significant attention, enabling cooperative behaviors where one robot (leader) dictates the trajectory, and others (followers) align based on predefined rules or real-time interactions. These formations can vary in structure, ranging from fixed geometries to adaptive and dynamic arrangements [3].

Communication between these robots is critical for maintaining the formations, with wireless methods such as WiFi, Bluetooth, and RF generally employed for their range, versatility, and the volume of data that can be passed through. However, IR-based communication offers distinct advantages, including low power consumption, minimal interference, precise directional signaling, and low development cost, making it particularly effective for a laboratory setting [4], [5].

The Pololu 3Pi+ is an affordable differential-drive robot equipped with various sensors, namely, line sensors, IR-based bump sensors for collision detection, and an Inertial Measurement Unit (IMU) [6]. The bump sensors, mounted at the front of the robot, consist of emitters on the top side of the PCB and receivers on the bottom. These sensors can operate in either analog or digital modes [7]. In analog mode, raw IR readings are directly acquired, while in digital mode, a timer-based method measures the capacitor's discharge time, which is influenced by the current controlled by the IR signal intensity. The IR light intensity and the bump sensor readings in digital mode exhibit an inverse relationship. As per the documentation, only the left bump sensor has been given the provision to operate in both modes, while the right bump sensor can only be operated in digital mode [6].

In the leader-follower setup, one robot assumes the leader role, while the other acts as the follower. Two simple configurations for this setup are outlined below.

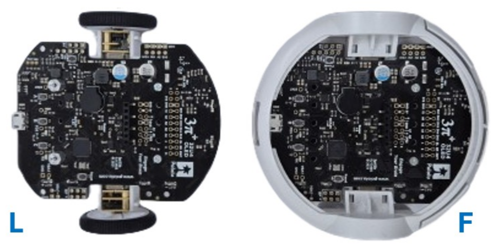

Fig. 1. Leader (L) - Follower (F): Straight-Approach.

A. Approach 1: Straight

Both robots are oriented in the same direction, with the leader encased in a plastic shell and the follower operating without one just as in Figure 1. The follower uses its front-mounted bump sensors to emit and receive IR light for tracking. A significant limitation of this approach is the curvature of the leader's shell, which causes IR light to scatter in multiple directions, increasing the likelihood of signal loss and tracking failure [5], [6].

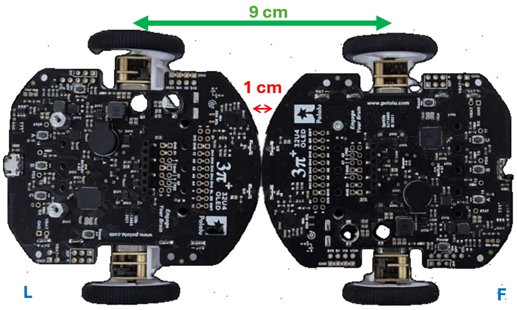

Fig. 2. Leader (L) - Follower (F): Facing-Approach

B. Approach 2: Facing

The robots face each other like in Figure 2, with the leader transmitting IR light through its bump emitters and the follower capturing it using its front-mounted bump sensors. This configuration reduces signal scattering and improves reliability, as the IR signal directly aligns with the follower's receiver. It is worth noting that the leader will be moving in reverse in contrast to the previous approach [4].

The primary objectives of this work are to determine the effective communication distance between the leader and follower robots using IR-based sensing and to establish the allowable range of in-place rotations of the leader within which the follower can reliably detect the IR signals. These parameters will be experimentally validated through tasks such as waypoint navigation to assess the accuracy of the communication system under dynamic conditions [1], [3].

The rest of this paper is structured as follows: Subsection C describes the hypothesis; Section 2 presents the implementation of the leader-follower setup; Section 3 presents the methodology undertaken step by step to achieve the objectives; Section 4 discusses the data obtained from the experiments, and finally section 5 concludes with the summary and the possible directions for the future.

C. Hypothesis Statements

i) Using IR Pulse emissions from the leader enables a smoother relation between bump sensor readings and the distance between the robots.

ii) Higher ON-time durations will discharge the capacitor quickly, leading to similar issues observed in continuous emissions. Conversely, very low ON-time durations may result in an inferior contribution compared to ambient light interference.

iii) The turning direction of the leader robot can be determined by analyzing the variation in the left and right bump sensor readings on the follower robot across varying angles. However, this relation will not be monotonic due to the orientation of the bump sensor receivers.

iv) Changes in illumination levels affect the performance of the leader-follower approach, with low light intensity expected to yield better results due to reduced ambient light interference.

II. Implementation

A. Robot Configurations

The setup involves two Pololu 3Pi+ robots in a **Facing Approach**, with one robot designated as the leader and the other as the follower:
The leader Robot emits IR signals and then the follower Robot detects IR signals using front-mounted bump sensors operating in digital mode.

A couple of standard experiments were conducted to narrow down the specifics of the setup, which are described below.

Experiment A: The bump sensors of the follower robot are not calibrated and made to operate only in ambient lighting conditions.

Observation A, ambient light was found to significantly influence the discharge rate of the follower robot's sensor capacitors, reducing their charge within approximately 6 milliseconds. This sensitivity highlights the need for precise and controlled IR emissions to ensure reliable operation.

Experiment B: The robots were setup in the **Facing-Approach** with the leader fixed in position while the follower was moved along a straight line directly facing the leader. The wheel-to-wheel distance between the robots varied from 9 cm to 19 cm. It's important to note that this means the distance between the bump sensors of the two robots was varied between 1 cm and 10 cm. This parameter (gap between the leader's bump sensors and follower's bump sensors) will be referred to as **separation** throughout this paper. The measurements taken for 0.1 ms pulse and continous emission are shown in Figure 2.

Observation B, continuous IR emissions from the leader robot resulted in rapid discharge of the follower's bump sensor capacitors, even at a separation of 10 cm. This behavior suggests that continuous emissions are less reliable for consistent proximity-based communication, particularly at closer separations.

Building on the above observations, the implementation consists of two Pololu 3Pi+ robots positioned to face each other. The leader robot follows its trajectory while simultaneously emitting signals for the follower to detect, maintaining a loop time of approximately 6ms. The follower robot strives to closely track the leader's movements.

III. Methodology

This section provides a detailed description of the experiments conducted along with the relavant metrics used to analyze the behavior of the leader-follower system in each of the experiments.

A. Discussion of Metrics

Metrics are crucial for quantifying system performance, and this study employed the following:

1) Alignment Error (E_A): This metric calculates the absolute of the difference in the left and right bump sensor readings:

$$E_A = |B_L - B_R| \tag{1}$$

where B_L and B_R represent the readings of the left and right bump sensors, respectively. An ideal alignment corresponds to $E_A = 0$.

2) Mean Trajectory Deviation (D_{mean}): The mean trajectory deviation is a critical metric for evaluating the alignment between the leader's and follower's paths. It is computed as the mean of the perpendicular distance between a point in the follower's trajectory from the leader's trajectory. It is given by,

$$D_{mean} = \frac{1}{N} \sum_{i=1}^{N} \frac{|ax_i + by_i + c|}{\sqrt{a^2 + b^2}} \tag{2}$$

Where:

- (x_i, y_i): Points on the follower's trajectory.
- a, b, c: Coefficients of the line segment representing the local trajectory of the leader.
- N: Number of points in the follower's trajectory.

B. Experiment Descriptions

Experiment 1 (Rectilinear): The same setup as Experiment B was followed, along with a goal to establish a relationship between the bump sensor readings and the separation between the robots, ultimately identifying an optimal distance range for practical use. The evaluation criterion was minimizing the alignment error, as ideal straight-line motion requires both sensors to provide equal readings for accurate alignment. The alignment error is defined by equation (1). This experiment was conducted for pulse durations from 0.1 ms to 1 ms and the continuous emission case as well.

Experiment 2 (Angular): The robots were configured in the Facing-Approach at a separation of 3 cm. The leader and follower were fixed in position, and the follower's orientation was also kept constant. The leader was rotated about the perimeter of a semi-circle of radius 3 cm from -80° to +80°. The primary objectives were to determine the maximum allowable angular range for reliable signal reception and to develop a method for the follower to classify the leader's turning direction based on variations in the left and right bump sensor readings. This experiment was conducted for pulse durations from 0.1 ms to 1 ms and the continuous emission case as well.

Experiment 3 (Illumination Variance): The robots were configured in the Facing-Approach and put to test for three different lighting conditions (1 lux, 250 lux and 650 lux). The leader was given a pre-defined trajectory to be executed at 17 PWM, along with 0.1 ms emission condition. The follower utilizes the logic specified in Algorithm 1 to achieve the task at 25 PWM. Under each illumination condition, 10 trials were conducted and the performance of path followed, was evaluated as the mean of trajectory deviations represented in equation (2). In each trial, both the leader and the follower record their positions via wheel-odometry and store it in a dynamic memory array at 2Hz frequency. By the end of each trial, the complete array is printed on the Serial monitor, which is then captured into an excel sheet through a python script. The Figure 7 shows the trajectory

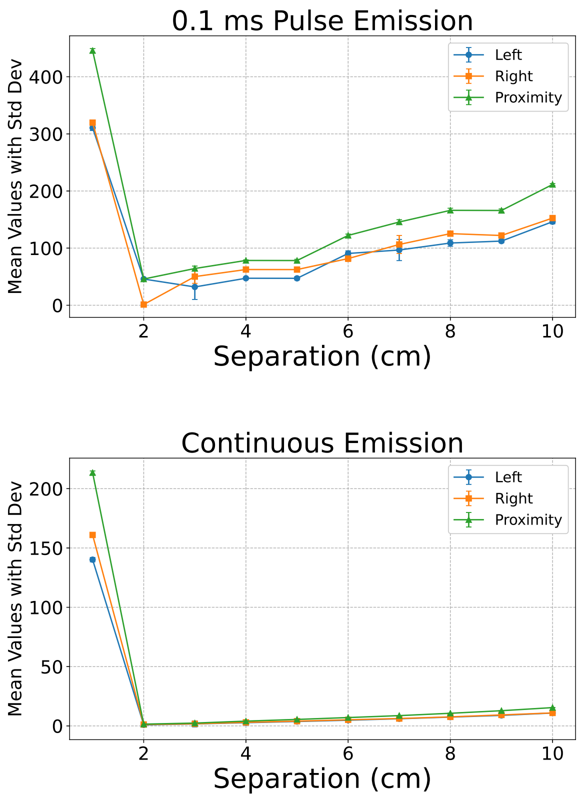

Fig. 3. Relation between bump sensor readings (100 μs) and the separation (cm) between the robots, for 0.1 ms pulse and continous emission respectively

of both leader and follower in one of the trials conducted under 250 lux condition.

Algorithm 1 Follower Pseudocode

$proximity \leftarrow \sqrt{(B_L^2 + B_R^2)}$
$ratio \leftarrow B_L/B_R$
if $proximity \geq 75$ **then**
  if $ratio > 1.0$ **then**
    turnRight()
  else if $ratio < 1.0$ **then**
    turnLeft()
  else
    moveFWD()
  end if
else
  stop()
end if

IV. Results and Discussion

The following observations were made based on the experiments conducted previously.

Observation 1: From Figure 3, it is evident that the bump sensor readings and proximity values are significantly higher and more noticeable across a wider range of separations when using the pulse method compared to continuous emission.

Observation 2: The bar chart in Figure 4 demonstrates the alignment error as a function of separation for various pulse emission types. At closer separations (2-4 cm), the alignment error is generally higher, particularly for 1 ms pulses, which consistently exhibit the largest errors across all separations. Continuous emission shows the smallest alignment error across most separations, particularly at larger distances (6-10 cm). The errors for 0.1 ms, 0.3 ms and 0.5 ms pulses show moderate performance, with errors reducing as the separation increases. Notably, alignment error stabilizes at larger separations with continuous emissions maintaining the lowest values indicating superior performance for maintaining a specific separation value. The optimal separation value appears to be between 3 cm and 8 cm.

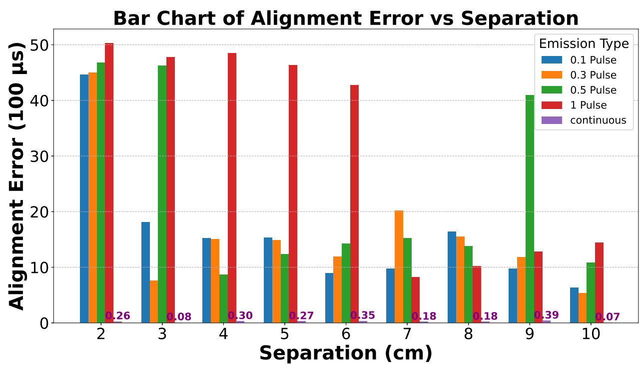

Fig. 4. Impact of pulse duration on alignment error across varying separation distances.

Observation 3: From Figure 5 and 6, It can be observed that the maximum range of turning angles for the leader, within which the follower can maintain track and distinguish turns, was observed to be between -50° and +50°. It's worth noting that negative angles mean the leader turns to the right, while positive angles mean the leader turns to the left. For pulse emissions the left and right turns of the leader can be quite easily classified in case of 0.1 and 0.3 compared to 0.5. In case of 0.1 ms pulse, although the two bump sensors yield similar values close to 0, the left sensor records a higher value compared to the right when the leader

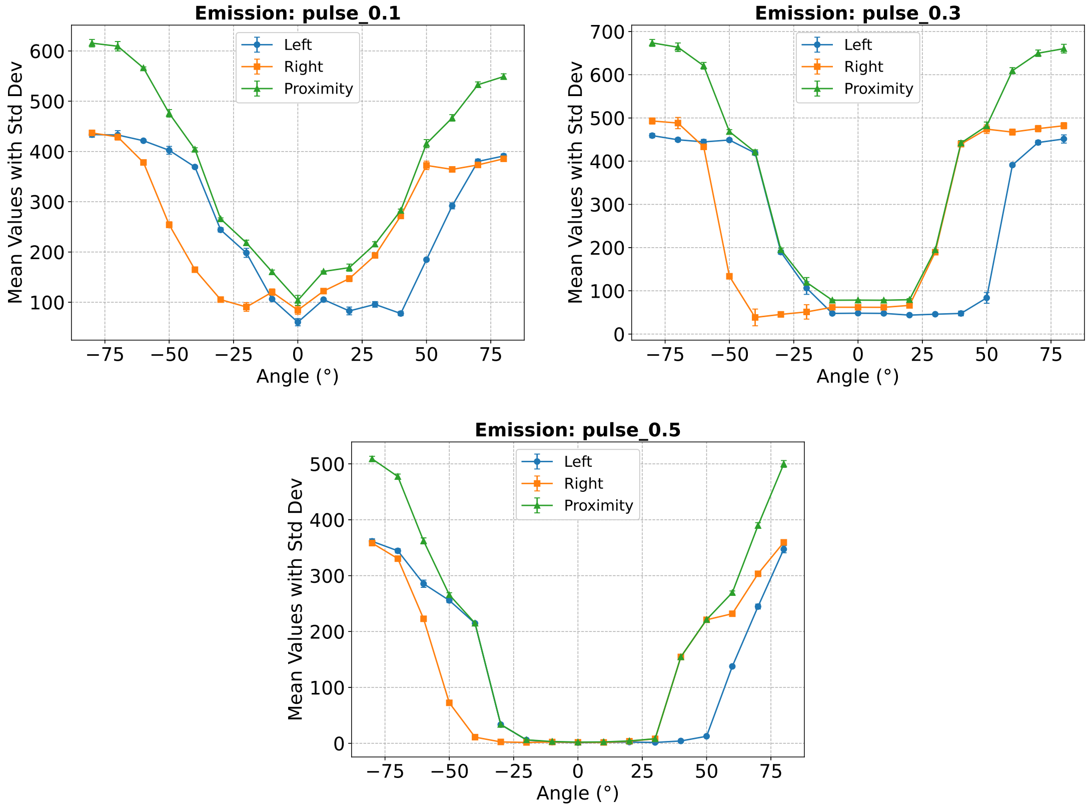

Fig. 5. Variation of Mean Values (100 μs) with Angle (°), illustrating proximity variations for intermediate pulse durations

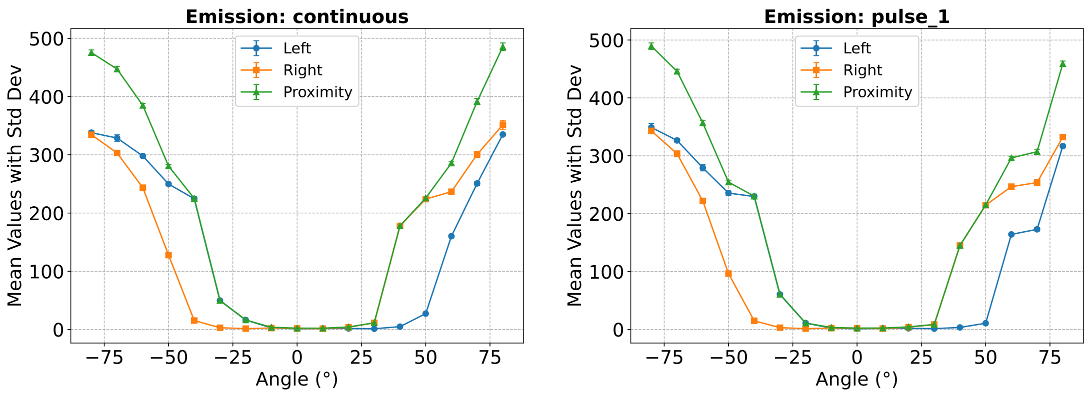

Fig. 6. Variation of Mean Values (100 μs) with Angle (°), for 1 ms Pulse and Continuous Emission.

turns right, this effect is quite significant below -10°. Similarly, the right sensor records a higher value compared to the left when the leader turns left, this effect is quite significant above +10°. Considering 10° as the breakpoint for 0.1 ms, taking a look at 0.3 ms emission, it can be found that the breakpoint to be around 15° to 20° and for 0.5 ms emission, the breakpoint is around 30°. A similar observation can be made with 1 ms and continuous emissions as well. It's critical to have a quicker breakpoint so that the follower doesn't have to wait long until it picks up data significant enough to classify the turning direction of the leader. This concludes 0.1 ms to be a good fit for both rectilinear and angular maneuvers compared to other pulse durations and continuous emission as well.

Observation 4: The Figure 8 represents a box plot for Experiment 3 under the lighting conditions 1 lux, 250 lux and 650 lux respectively. It can be observed that the median value is the least for low ambient lighting conditions and is the highest for higher illumination. For the case of 250 lux, the median value is in between the others. However, it's clear that under

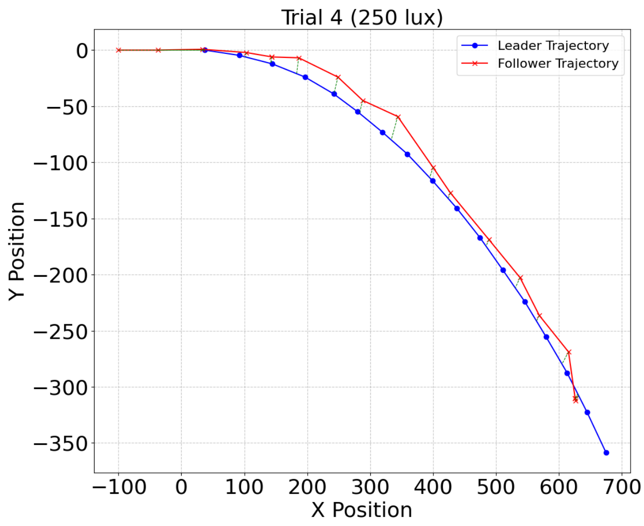

Fig. 7. Leader vs Follower Path at 250 Lux. Comparing the trajectories under normal lighting conditions (dimensions in mm).

normal light (250 lux), the variance in the data is really low compared to brighter or dimmer conditions, hence proving its reliability for the leader-follower setup.

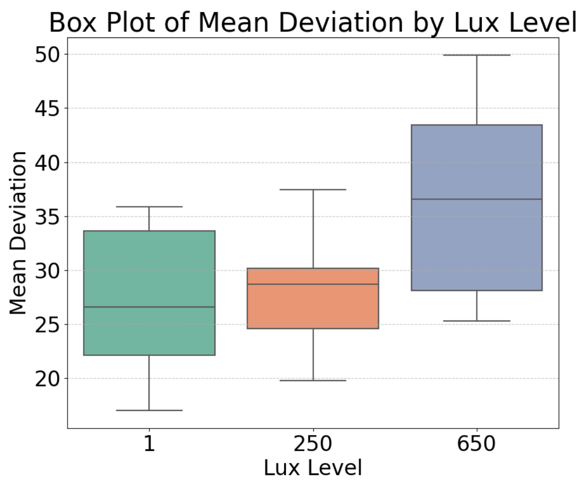

Fig. 8. Box Plot of Mean Trajectory Deviation (mm) by Lux Level. This figure demonstrates the impact of ambient light levels on tracking reliability.

V. Conclusion

This study confirmed that pulse method provided significantly higher and more noticeable proximity values across a broader range of separations compared to continuous emissions which is quite in favour of the first hypothesis. Next, It was expected to have poor results with either too high or too low duty cycle pulses. From the experiments it was noted that alignment errors were highest with 1 ms pulses at close separations, thereby supporting a part of the expectation. However, pulse durations of 0.1, 0.3, and 0.5 ms showed decreasing errors as separation increased. This deviation in inference led to experiments for angular maneuvers, where it was assumed that leader turning direction can be inferred from the bump sensors variations. Pulse emissions, especially at 0.1 and 0.3 ms, allowed reliable classification of turns with quicker breakpoints. Considering both rectilinear and angular plots, 0.1 ms pulse was deemed suitable for the leader follower setup. The final test involved evaluation of follower performance when the leader executes a pre-defined trajectory. This was conducted under 3 illumination conditions with the prediction that lower illumination improves leader-follower performance due to reduced ambient light interference. Under normal lighting (250 lux), data variance was observed to be minimal, enhancing reliability compared to brighter or dimmer conditions. These findings highlight the effectiveness of pulse-based IR emissions and optimal lighting conditions for robust alignment and tracking.

VI. Future Work

A significant improvement to this work could be is to evaluate the leader-follower formation under varying leader trajectories and speeds to analyze system performance, robustness, and adaptability in diverse dynamic scenarios.

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