Leader-Follower Formation and Obstacle Avoidance for Nonholonomic Mobile Robots Using Velocity Obstacles

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***Abstract*— A multi-robot system is a group of robots that coordinate and perform complex tasks with the help of a communication system. The commonly adapted approaches in multi-robot formation control include the leader-follower method, where the leading robot acts as the coordination center, and follower robots track the movement of the leading robot. Multi-robot formations often encounter both static and dynamic obstacles in their operational environment. This paper proposes a novel strategy that combines leader-follower formation control with the Velocity Obstacle-based obstacle avoidance algorithm for mobile robots. The proposed strategy allows each robot to keep its position in a flexible formation while autonomously avoiding obstacles, which guarantees a robust performance in dynamic environments where there are moving obstacles. Different obstacle configurations relative to the x-axis at 0, -45, and -90 degrees were performed in simulation. The results of the simulation runs reveal the capabilities of the multi-robot system for maintaining formation and avoiding both static and dynamic obstacles. The leader-follower system had minimal position errors within the 0-degree scenario, with the least error from Robot 3 at 0.627 meters. The algorithm avoided collision in all scenarios for Velocity Obstacle.**

Keywords*— *leader-follower, nonholonomic mobile robots, obstacle avoidance, robot formation, velocity obstacles.

I. INTRODUCTION

It is now modern robotics that has brought a new era to multi-agent robotic systems, where collaboration of task completion is made possible by the coordination among multiple robots effectively [1]. Indeed, these systems are competent in complex tasks, with each unit specializing in specific functions [2]. However, the most basic problem of mobile robots, especially when they need to share an area with humans, is to navigate with the ability not to cause risks or disturbances to humans or objects that surround them [3].

In dynamic areas, safety and comfort must be stressed[4]. Mobile robots must not hurt a human and must be able to avoid static and dynamic obstacles in their path [5]. This dual requirement of human safety and obstacle avoidance has led to the development of various navigation strategies [6]. Nonholonomic mobile robots [7], which are characterized by constraints on their motion due to their wheel configurations, cannot move in arbitrary directions instantaneously.

Obstacle avoidance approaches can normally be distinguished into two sets [8]. The first one translates sensor data using heuristic methods - such as Bug [9], Bubble [10], Gradient Method or physics-inspired techniques such as the Artificial Potential Field [11]- into motion commands [12]. The other set generates a set of velocity commands; this is explained with methods such as the Curvature Velocity Method [13], Dynamic Window Approach [14], and Velocity Obstacle [14][15].

Recent research has concentrated on these methods in different contexts. For instance, Boldrer et al. [16] have used the Velocity Obstacle for navigation in a tightly crowded environment to avoid dynamic and static obstacles. Van den Berg et al. [17] have used an extension of the Velocity Obstacle called RVO for moving more stably to avoid obstacles. However, none of their research covered the field of maintaining geometric formations by mobile robots. In a different approach, Zhang and Liu [18] applied the leader-follower method for multi-robot formation control, but this study did not incorporate obstacle avoidance. In addition, Zulkarnain [19] also applied the leader-follower method for formation control and obstacle avoidance using CTC, but this study has not addressed dynamic obstacles.

These challenges can be offset by presenting a new approach that merges the leader-follower formation technique with Velocity Obstacles-based obstacle avoidance. Such a combined approach would provide a solution for keeping nonholonomic robots in formation while avoiding obstacles.

The advantages of both control methods are combined in the proposed approach. On the one hand, leader-follower formation control is more structured when generating coordination among multiple robots. On the other hand, the Velocity Obstacle algorithm enables local navigation and collision avoidance. We blend these two techniques to devise a system that can maintain enforcement while successfully navigating through complex, dynamic environments with many obstacles.

This research is expected to fill one of the most critical gaps in multi-robot systems by providing a navigation strategy that can maintain the integrity of a formation and still guarantee collision-free movement. The outcomes of this research could have very diverse applications, from warehouse automation and search and rescue to collaborative exploration tasks in unfamiliar or hazardous environments.

The paper is organized as follows: Section II discusses the methods used in obstacle avoidance planning with velocity obstacles and leader-follower formation. In Section III, the results of Matlab simulations conducted according to the proposed methods are presented. Finally, the paper is concluded, with probable future research directions outlined, in Section IV.

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II. Methods

Block diagram modeling of navigation, including leader and follower robots, is taken from research. Independently, each robot performs its tasks while in collaboration keeps the formation and avoids obstacles within its environment. The leader robot determines the direction and destination of the formation. Its position and orientation serve as reference data for follower robots. Follower robots are the robots which determine their moves according to the position of the leading robot, keep the formation without hitting any obstacle, based on the position update from the leader on their target position.

Fig. 1 depicts the block diagram control system for the leader robot, which uses a combination of the pure pursuit algorithm for path planning and velocity obstacles for collision avoidance, allowing it to navigate towards a target while avoiding obstacles. Fig. 2 shows the block diagram control system for the follower robot, which maintains a specific formation relative to the leader, using the velocity obstacle method to avoid obstacles and stay in position. Both diagrams highlight the modular structure of the systems, showing how each robot adapts to its environment to move safely and in coordination with the other. A block diagram is a simplified representation of a system that shows its main components and how they interact.

This work proposes a simulation-based approach to modeling nonholonomic mobile robots in leader-follower formation by incorporating the Velocity Obstacles algorithm for obstacle avoidance. The main methodologies adopted in research are presented in the following steps.

A. Kinematic Mobile Robot

In a differential drive robot, two separate controllable wheels are often mounted on each side of the robot. This enables the robot to move forward, backward, or even turn if one wheel's speed varies. When both wheels rotate at the same speed, the robot then moves in a straight line. On the other hand, if one wheel rotates faster compared to its opposite wheel, then it turns to the slower wheel.

Motion is constrained by kinematic equations mapping linear and angular velocities into position and orientation, presented by Fig. 3. The forward kinematics can be represented as follows: Pure Pursuit assumes an attached reference coordinate system in the form of input processing and output generation. The velocity command for the robot that is generated makes use of the algorithms.

$$v = \frac{R}{2}(\omega_R + \omega_L), \qquad \omega = \frac{R}{L}(\omega_R - \omega_L) \tag{1}$$

The inverse kinematics are defined as follows:

$$\omega_L = \frac{1}{R}\left(v_{ref} - \frac{\omega_L}{2}\right), \qquad \omega_R = \frac{1}{R}\left(v_{ref} + \frac{\omega_L}{2}\right) \tag{2}$$

where the linear velocity v and the angular velocity ω of the robot are related to the angular velocities of the right wheel ω_R and the left wheel ω_L, with R being the wheel radius and L the robot's dimensions.

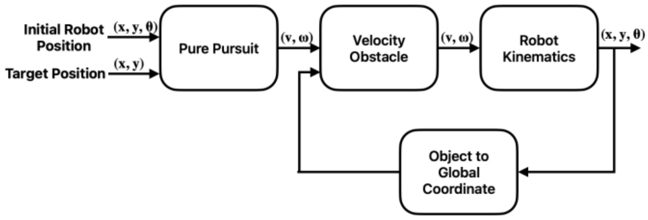


Fig. 1. Block Diagram for the Leader Robot

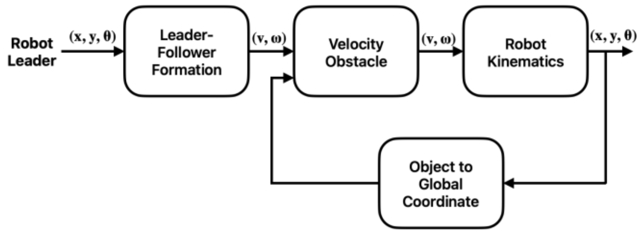


Fig. 2. Block Diagram for the Follower Robots

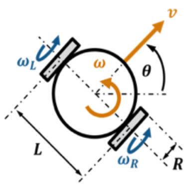


Fig. 3. Mobile Robot

B. Pure Pursuit

Pure Pursuit assumes attached reference coordinate system form for input processing and output generation, where the generated velocity command for the robot uses the algorithms. The input waypoints are on the coordinate forms that this algorithm will use to generate the velocity command for the robot. Position and orientation represent the pose of the robot, where the angle θ represents the orientation of the robot measured counterclockwise from the positive x-axis (0 radians). This is shown in Fig. 4.

The angle α is to be determined between the axis of orientation of the robot and the straight line joining the robot to the look-ahead distance L_d. Therefore, considering the robot's orientation, with (x, y) being the position of the robot and (x_T, y_T) being the position of the target, and the angle of the robot with respect to the target θ_T, the value of α becomes:

$$\alpha = \arctan\left(\frac{y_T - y}{x_T - x}\right) - \theta_T \tag{3}$$

Based on the desired trajectory of the robot and its current estimate of pose, the linear velocity v and angular velocity ω are computed.

$$v = \min\left(\frac{d}{t}, v_{max}\right), \quad \omega = v\,\frac{2\,v\sin(\alpha)}{L_d} \tag{4}$$

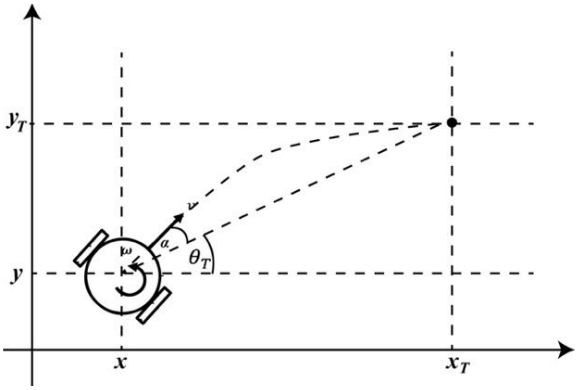


Fig. 4. Pure Pursuit

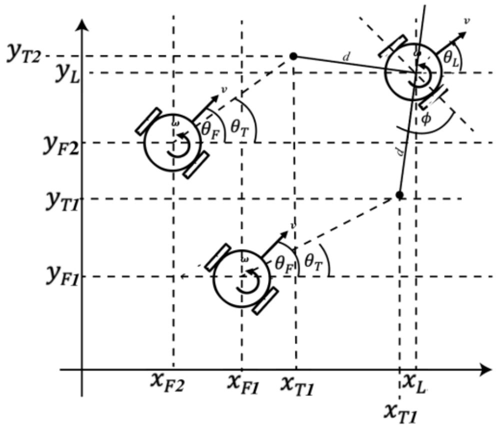


Fig. 5. Formation Control

C. Formation Control

The V-formation is used as the basis of the leader-follower formation control approach. Follower robots will be allowed to readjust position and orientation using global data provided by the leading robot. To obtain a stable V-formation, the computation of target positions for followers will be done based on distance and relative orientation with respect to the leading robot.

The desired position of each follower robot is defined relative to the position and orientation of the leader globally [20]. Let the position of the leading robot be (x_L, y_L), where θ_L is its orientation. The desired distance d between the leader and followers, and the preferred formation angle ϕ, will define the target positions of the left and right followers as shown in Fig. 5.

For the follower, the target position (x_T, y_T) is computed as:

$$x_T = x_L - d\cos(\theta_L \pm \phi) \quad (5)$$

$$y_T = y_L - d\sin(\theta_L \pm \phi) \quad (6)$$

Once the target positions of all followers are known, the next step is calculating the distance l and angle θ_T from the current position of each follower to its target.

$$l_x = x_T - x_F \quad (7)$$

$$l_y = y_T - y_F \quad (8)$$

$$l = \sqrt{l_x^2 + l_y^2} \quad (9)$$

It is more precisely that the target angle θ_T represents the direction from the position of a follower towards a target.

$$\theta_T = \text{atan}^{-1}\left(\frac{l_x}{l_y}\right) \quad (10)$$

For reaching the target, the difference of the orientation angle α is determined by measuring the current orientation of the follower with respect to the direction toward the target position.

$$\alpha = \theta_F - \theta_T \quad (11)$$

This is done by computing the difference between the current orientation of the follower and the direction towards the target, its orientation angle difference α, to reach it. The reference linear velocity, v, for the follower is calculated based on the distance towards the target, given the time interval t, and saturated by the maximum allowed speed defined by v_{max}. In terms of angular movement, pure pursuit control, a classic approach to achieve tracking in mobile robotics is used to compute the reference angular velocity ω that helps the follower change its orientation to minimize α during its approach to the target.

D. Velocity Obstacle

The key algorithm presented in this paper seeks to compute safe, optimal linear v and angular ω velocities for each robot, that guarantee the avoidance of collision with obstacles. Its approach is in sampling a discrete set of velocities, evaluating each velocity using the Velocity Obstacle cone as shown in Fig. 6. Multiple input sources are considered in the algorithm to include the position of the robot, current velocity, target position, and positions and velocities of obstacles to ensure efficient and effective robot control solutions as shown in Fig. 7.

It then initializes some important parameters like the position of the robot, linear and angular velocities, the position of obstacles around it, and velocity. Other parameters involve setting a safety radius and bounds on maximum velocity considering safe operation. It then generates samples of possible velocities and, for each of these, considers nearby obstacles by calculating their positions and velocities relative to the robot.

The VO cone is defined mathematically:

$$VO_A^B(v_B) = v_A | \lambda(P_A, v_A - v_B) \cap (B \oplus -A) \neq \emptyset \quad (12)$$

where VO_A^B is the set of velocities v_B of object B that will cause a collision with object A, assuming A moves at velocity v_A. This set is computed as the relative trajectory $\lambda(P_A, v_A - v_B)$ that intersects with the Minkowski operation between B and A.

Using trigonometric functions, left and right boundaries are set using trigonometric functions and checks each sampled velocity if it lies within this cone. If a sampled velocity falls inside the VO cone, it is marked unsafe, and the algorithm tests the next sample. In case of sampled velocity lying outside the VO cone, penalties are computed distance to the optimum selected velocity and consistency with the target direction. The optimal and safe for the robot is the one with minimum penalty. Thus, v_{safe} and ω_{safe} can be determined for obstacle avoidance.

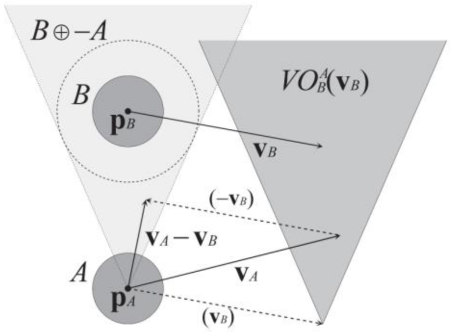


Fig. 6. Velocity Obstacle Collision cone

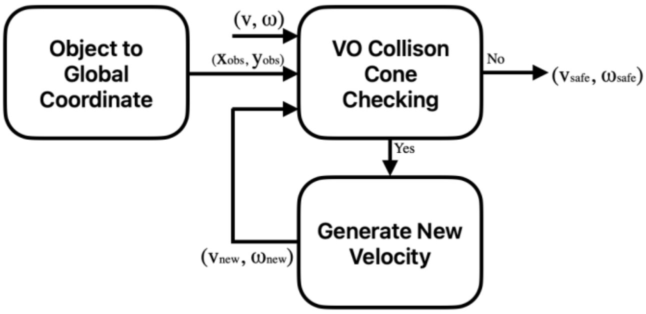


Fig. 7. Velocity Obstacle

E. Simulation Design

The simulation design is performed for testing the performance of obstacle avoidance and robot formation algorithms under different scenarios, which can realistically engage in methodologies related to real-world conditions. Various simulations are carried out using Matlab software in order to study the capability of mobile robots to adapt to dynamic situations, such as with humans and other objects. Three scenarios are prepared to test the control algorithm: first, the robot faces an obstacle directly from the front at 0°, simulating the challenge of avoidance while following a straight path. Second, the robot faces an obstacle at an angle of -45°; here, the system has to predict the trajectory of the human group while maintaining formation. The third case is when the robot moves perpendicular to the human at an angle of -90°, and in this case, the robot has to make a dynamic decision to cross the human path safely.

III. RESULTS AND DISCUSSION

In this section, we would like to explain what we have implemented in our multi-robot navigation and formation across three scenarios. These three scenarios were conducted to assess the response of the multi-robot system when encountering obstacles positioned in straight lines, diagonally, and perpendicularly.

The simulations were carried out in MATLAB using parameters for the mobile robots, including the number of mobile robots, the diameter of the robots, and other relevant factors, as shown in Table I.

TABLE I. PARAMETERS FOR MOBILE ROBOT SIMULATION

Parameters	Value
Number of Robots	3
Number of Human	2
Number of Static Obstacle	2
Robot Wheelbase	0.5 m
Maximum Linear Velocity for Leader	0.5 m/s
Maximum Linear Velocity for Followers	6.5 m/s
Maximum Angular Velocity	1 rad/s
Simulation Time Step	0.1s

A. First Scenario

In the first scenario, the robots form a formation and then approach the human from a 0-degree angle relative to the x-axis as shown in Fig. 10. In this experiment, it was observed that the multi-robot system avoided both static and dynamic obstacles that appeared at 0-degree angles. To evaluate formation accuracy, position error was used, representing the difference between the target position of the follower robot and the actual position of the follower, as shown in Fig. 8. Meanwhile, the response or changes in the speed of the mobile robots are illustrated in Fig. 9.

The Table II presents some performance information for three robots constituting a multi-robot system. This plot sums up the mean linear velocity of the robots: the mean velocity is taken to be 0.438 m/s for Robot 1, 0.488 m/s for Robot 2, and 0.466 m/s for Robot 3. From this, the angular velocities for all robots are almost zero or much negligible, hence proving that indeed there was little or no rotation during the execution of the task. It also gives the total distance covered by each robot; the distance covered by Robot 2 is 17.113 meters, the longest in comparison to others. Target time taken by Robot 1 30.7 s.

The same approach also underlines one more very important element, the position error of the formation, which is the Estimation of the difference between the real positions of the robots-followers and their expected ones in the formation. While in the experiment the position error for Robot 2 was 1.236 meters, Robot 3 had a relatively lower error of 0.627 meters. This indeed proved that Robot 3 was closer to the intended formation than Robot 2. Such a position error occurred because both the follower robots had to negotiate their ways around obstacles along their paths. Throughout this task, all three robots did not collide, with zero collisions recorded.

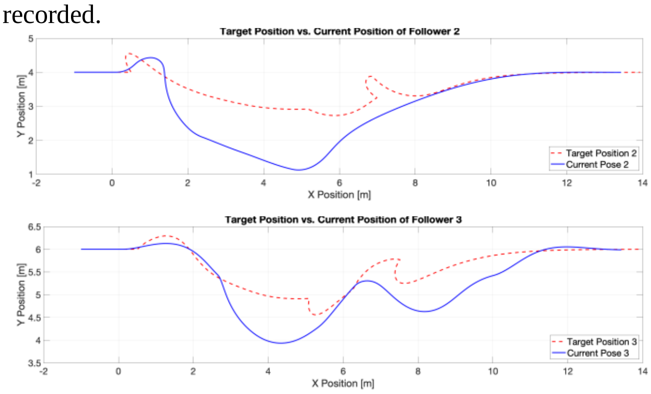


Fig. 8. Position Error of Follower Robot at 0-degrees

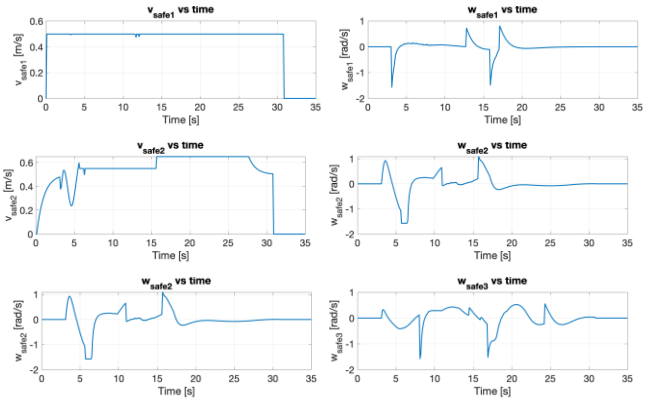


Fig. 9. Linear and Angular Velocity at 0-degrees

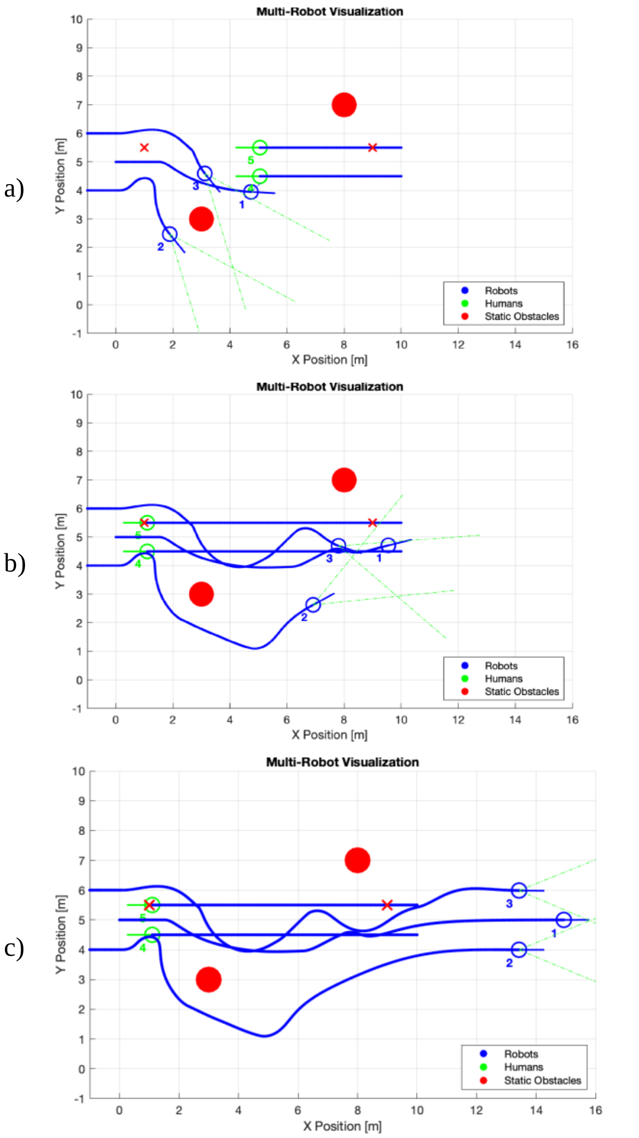


Fig. 10. Multi-robot Visualization at a 0-degrees, a) at $t = 10s$ b) $t = 20s$ c) $t = end$

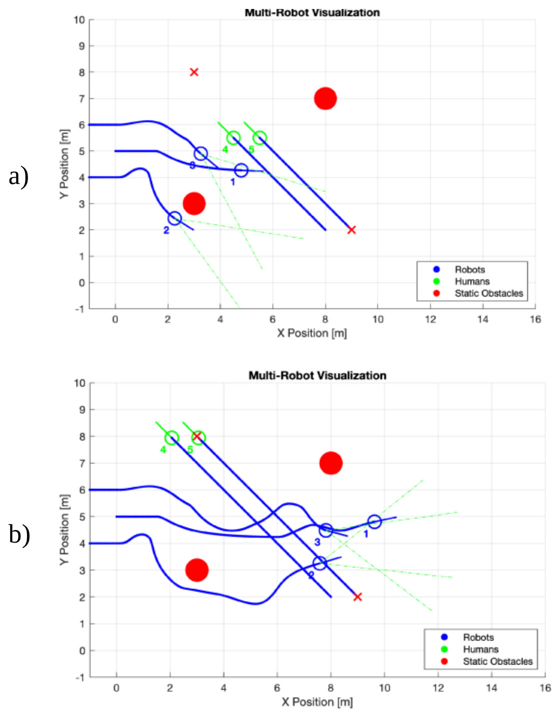
TABLE II. MULTI-ROBOT PERFORMANCE WHEN ENCOUNTERING OBSTACLES AT 0 DEGREES

	Robot 1	Robot 2	Robot 3
Average of Linear Velocity (m/s)	0.438	0.488	0.466
Average of Angular Velocity (rad/s)	0.00	0.00	-0.000
Distance (m)	15.365	17.113	16.365
Time to Target (s)	30.7	-	-
Error Formation Position (m)	-	1.236	0.627
Number of Collisions	0	0	0

B. *Second Scenario*

In the second scenario, robots will form exactly as described above, but move into the human at an angle of -45 degrees relative to the x-axis. The change in angle challenges the analysis, whereby for diagonals, the robots have to adjust both formation and path to meet the movement.

In this experiment, it was determined that the multi-robot system successfully avoided both static and dynamic obstacles encountered at a 0-degree angle as shown in Fig. 11. Furthermore, to assess the formation established, position error, The position error, which is defined as the discrepancy between the follower robot's target position and its actual position, was employed, as shown in Fig. 12. Additionally, Fig. 13 shows the response of each mobile robot during movement. The changes in angular velocity indicate how the mobile robots perform obstacle avoidance maneuvers.



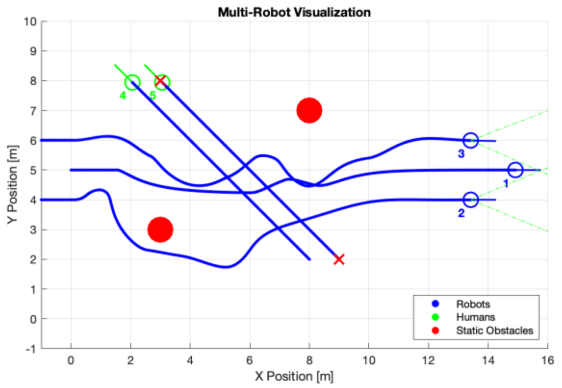
c) 

Fig. 11. Multi-robot Visualization at a 45-degrees, a) at $t = 10s$ b) $t = 20s$ c) $t = end$

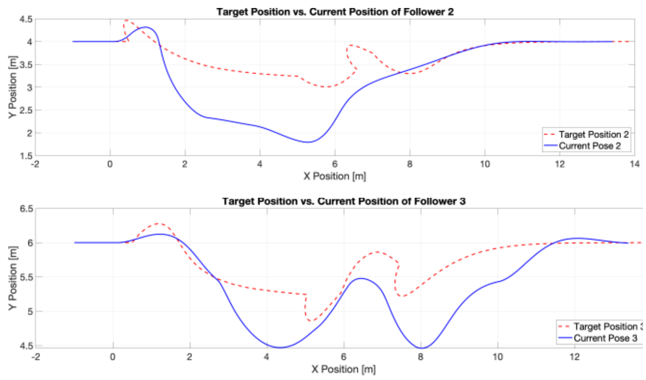


Fig. 12. Position Error of Follower Robot at 45-degrees

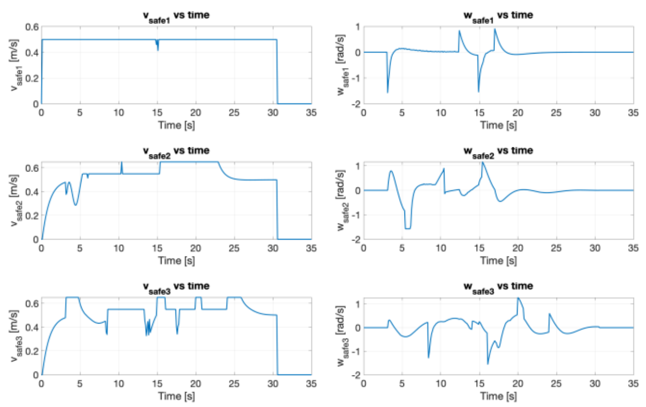


Fig. 13. Linear Velocity and Angular Velocity at a 45-degrees

Performances of all three robots in the multi-robot system shall be based on the basis of movement and obstacle avoidance as shown in Table III. Hence, the average linear velocity was 0.434 m/s, 0.465 m/s, and for Robot 3, it was 0.456 m/s. Angular velocities considered rotational velocities for Robot 1 and Robot 2 were zero, while for Robot 3, it was very small at -0.001 rad/s. The distances covered by each robot also show up; the maximum distance covered out of these will be 16.312 meters for Robot 2. Counted among these, the time to reach the target for only Robot 1 has been included, which is considered 30.4 seconds, while the rest of the robots' times are not available.

TABLE III. MULTI-ROBOT PERFORMANCE WHEN ENCOUNTERING OBSTACLES AT 45 DEGREES

	Robot 1	**Robot 2**	**Robot 3**
Average of Linear Velocity (m/s)	0.434	0.465	0.456
Average of Angular Velocity (rad/s)	0.00	0.00	-0.001
Distance (m)	15.234	16.312	16.015
Time to Target (s)	30.4	-	-
Error Formation Position (m)	-	0.194	0.610
Number of Collisions	0	0	0

In the formation, Robot 2 exhibited a relatively small position error of 0.194 meters, remaining very close to the calculated path. On the other hand, Robot 3 had a relatively larger error, indicated by a wider spread. This positional offset became worse during the obstacle avoidance phase, but slowly corrected after the robot finished navigating. These results show that even if the alignment was temporarily mismatched, the system eventually restored system alignment and avoided collision after having gone around obstacles.

C. *Third Scenario*

Third, in the case of a human-robot meeting at an angle of 90 degrees to the x-axis, the movement is perpendicular to the original direction, as shown in Fig. 16. Such a setting provides us with the ability to assess how the robot formation is capable of dealing with sharp directional changes and what consequences this may have on stability, response time, and coordination. The conditions of these three scenarios enable insight into the dynamics of the movement of robots and the adjustment of the formations under different angles.

This experiment was demonstrated when the multi-robot system was able to successfully avoid both a static and dynamic obstacle with the lateral distance showed in a change of 90 degrees. During formation evaluation for position error as shown in Fig. 14. Position error was defined as the distance from the target position of the follower robot to the actual position of the follower robot. The response or change in the speed of mobile robots is illustrated in Fig. 15.

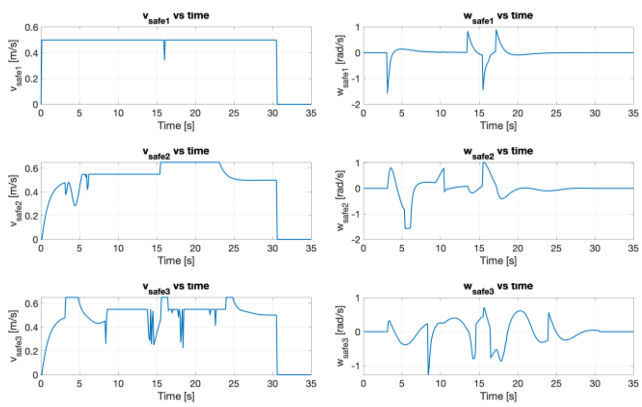


Fig. 14. Linear velocity and Angular Velocity at 90-degrees

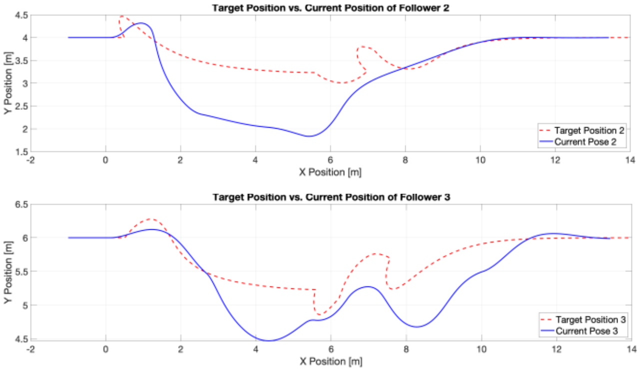


Fig. 15. Position Error of Follower Robot at 90-degrees

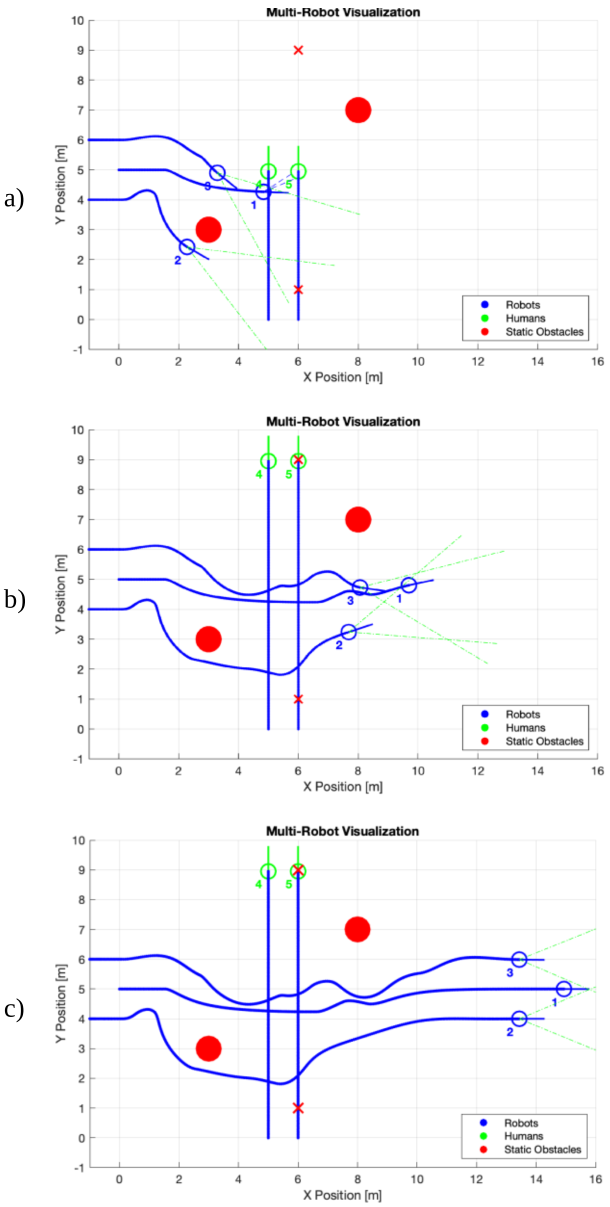


Fig. 16. Multi-robot Visualization at a 90-degrees, a) at $t = 10s$ b) $t = 20s$ c) $t = end$

Performance data for three robots in a multi-robot system is shown in Table IV. It shows the average linear velocities of the robots, with Robot 1 traveling at 0.434 m/s, Robot 2 at 0.463 m/s, and Robot 3 at 0.446 m/s. All three robots recorded zero angular velocity (0.00 rad/s), indicating they moved in a straight line without any rotation. The total distances covered by each robot are also given: Robot 2, 16.257 meters; Robot 3, 15.663 meters; Robot 1, 15.242 meters. The time taken to reach the target is only documented for Robot 1, which took 30.4 seconds, while data for Robot 2 and Robot 3 is not available. Robot 2 traveled 0.89 meters to the leader, whereas Robot 3, with only 0.564 meters, was the one that kept the closest formation. Moreover, the total number of collisions was zero for all robots, indicating that each robot successfully moved around obstacles without collisions.

TABLE IV. MULTI-ROBOT PERFORMANCE WHEN ENCOUNTERING OBSTACLES AT 90 DEGREES

	Robot 1	Robot 2	Robot 3
Average of Linear Velocity (m/s)	0.434	0.463	0.446
Average of Angular Velocity (rad/s)	0.00	0.00	0.00
Distance (m)	15.242	16.257	15.663
Time to Target (s)	30.4	-	-
Error Formation Position (m)	-	0.89	0.564
Number of Collisions	0	0	0

In general, the performance of the robots was highly effective regarding velocity control, there were similar linear velocities in all scenarios, which can be considered indicative that the control system can adapt to various movement patterns. Minor deviation of angular velocities further proves how well the system changes direction and keeps formation. The stability in the distances between followers and leaders for all scenarios, even for the more complex movements, proves that using a leader-follower control strategy does not sacrifice efficiency in maintaining a formation. No collisions in any case confirm that the Velocity Obstacle algorithm works well to make robots avoid static and dynamic obstacles while successfully following a planned path.

IV. CONCLUSION

This research proposes a new strategy that can incorporate the control of leader-follower formations into the Velocity Obstacle-based obstacle avoidance strategy for mobile robots. Major contributions of this work are to highlight that, within a flexible approach, each robot could keep the formation by itself, avoiding obstacles, and perform a robust integration of formation control with obstacle avoidance in different scenarios of simulations, even including dynamic environments with moving obstacles.

In the end, the tested multi-robot system could successfully show that it was able to do the maintenance of formation and avoid both static and dynamic obstacles at angles of 0, -45, and 90 degrees with respect to the x-axis. The leader-follower control system, granted positions of the follower robots that were close to the target formation with low position errors, as in the 0-degree scenario where Robot 3 had the smallest position error of 0.627 meters. Besides, the Velocity Obstacle algorithm proved capable of avoiding both static and dynamic obstacles, as evidenced in the fact that no collisions are recorded in any of the scenarios. Further development might complement the present results by addressing such aspects as development of more complex algorithm elaboration for formations shapes, introduction of sensor uncertainty, and applying physical robots in realistic environmental conditions.

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