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METHOD OF COORDINATION OF MOTION OF SWARM ROBOTIC SYSTEMS

Abstract: This paper proposes a method for coordinating the motion of swarm robotic systems while maintaining a specific geometric formation and ensuring obstacle and collision avoidance. The method uses a Leader-Follower approach with a virtual leader, which improves the fault tolerance of the system. The use of a virtual leader provides increased fault tolerance to the system, ensuring that even if the designated leader fails, the swarm can continue to operate effectively. The proposed method ensures that the swarm of robots maintains the desired formation while avoiding obstacles and collisions. The method's ability to reduce power consumption is achieved by turning on rangefinders only when necessary.

The performance of the proposed method is demonstrated through simulations of a swarm of nine robots. The simulations are carried out in different scenarios with various geometric patterns, indicating that the proposed method is scalable and can be extended to different swarm sizes and geometric formations.

The proposed method provides an effective solution for controlling a group of autonomous mobile robots to maintain a certain geometric pattern while ensuring obstacle and collision avoidance. The method has the potential to be used in numerous applications where multiple robots must work together to achieve a common goal while maintaining a specific formation, such as military missions and traffic management systems.

In summary, the proposed method uses a Leader-Follower approach with a virtual leader to ensure fault tolerance and maintain a specific geometric formation while avoiding obstacles and collisions. The method is scalable and can be extended to different swarm sizes and geometric formations. The method's ability to reduce power consumption is achieved by turning on rangefinders only when necessary.

Keywords: robotic swarm, formation control, leader-follower, coordination

Introduction

Nowadays, robotics is developing very strongly. Applications of robotics are especially relevant in areas of life where human activities are either difficult or impossible at all [1]. These areas may include combat conditions, research at the bottom of the oceans, research and exploration in space, and other similar scenarios.

Numerous strategies have been proposed throughout the history of robotics to enhance the capabilities of robots and address specific challenges in the industry. For instance, the implementation of navigation systems was provided in an article [2], while optimal models for transport were offered in another article [3]. An article [4] discusses challenges in IoT communications, while a different article [5] proposes the use of lightweight cryptography for IoT devices. Lastly, the potential use of blockchain technology in education as a strategy for enhancing robot capabilities was analyzed in an article [6].

As robots has evolved, many different approaches have been proposed to improve robot action. One of them is to use a group of several simple robots for a single complex task. The approach is known as group robotics.

Group robotics is a field of study aimed at developing robotic systems that can work collaboratively in a manner similar to animal groups. This field draws inspiration from various animal groups, including bees, ants, fish schools, bird flocks, bacteria, and slime molds. For instance, work by [7] presents an artificial bee colony algorithm for calculating the inverse kinematics solution of a 7-DOF robot manipulator. Work by [8] proposes aging-based ant colony optimization algorithms for grid-based mobile robot path planning in static and dynamic environments. In addition, work by [9] provides path planning and smoothing techniques for mobile robots based on an improved artificial fish swarm algorithm. Work by [10] offers a coordination algorithm for 3D underwater collective behaviors in a fish-inspired robot swarm, while work by [11] defines a programmable self-assembly technique in a thousand-robot swarm inspired by bird flocking. Moreover, work by [12] applies bacterial quorum sensing to the coordination of autonomous robot swarms, and work by [13] implements a modified swarm intelligence algorithm based on slime molds for path planning and obstacle avoidance in mobile robots.

Such an idea of solving complex problems by using several relatively simple robots has long been in the focus of researchers' attention. The earliest achievements in the form of actual projects in the group robotics field originated about three decades ago [14]. Currently, examples of group robotics applications are, for example, mobile robots, drones, satellites, etc.

The coordination and control of motion of the group is a major task of group robotics. In practice, to coordinate the motion of the robots in the system, the robots form some geometric structure while maintaining a distance between them [15].

Formation control is a control technique aimed at achieving certain shapes by a group of robots [16]. Here, robots can move without collisions, while forming a certain shape block to improve the performance of the whole system [17].

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Problem formulation

In many applications, groups of autonomous robots must follow a given path keeping a certain geometric pattern. If it is properly organized, many benefits can be obtained such as reduced system cost and increased system reliability and efficiency while providing the reconfigurable and flexible structure of the system.

Motion with maintaining certain geometric patterns is widely used. For instance, during military missions, unmanned vehicles must maintain a certain formation to cover the terrain and perform exploration. Also, in "The Smart Highways" the capacity of the traffic system can be significantly increased if vehicles can move forming groups at the same speed while maintaining a certain distance between them.

This paper presents a method for controlling a group of autonomous mobile robots to maintain a certain geometric pattern. The developed method makes it possible to move toward the target without colliding with an obstacle, while reducing the power consumption of rangefinders. The leader-follower approach was used to coordinate the movements.

Switching the rangefinder on and off

Modern rangefinders can detect obstacles far enough away. It is possible to find rangefinders that can sense ranges that are several times larger than the size of the swarm itself. But such rangefinders waste a lot of power. And in order to deal with this problem and to reduce power consumption, robots can, whenever possible, turn off their rangefinders and orient themselves to the movements of their neighbors. That is, for example, agents moving in the middle or behind can be guided by their neighbors who move right in front of them. In the method described in this article, the swarm movement, turns on the rangefinders only as required and thus reduces the power consumption.

Leader-Follower approach

The core idea of the leader-follower approach is that the follower robots try to keep the required distance the whole time. By representing the Leader and Followers as points on the surface and having the pose of each point, it is able to evaluate the distance between them. This distance can be used as a range that the follower tries to keep (Fig. 1).

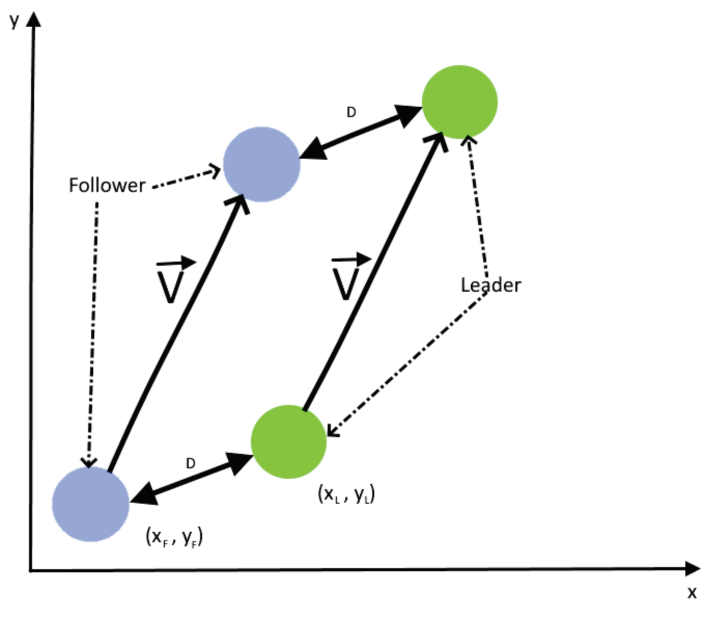

Figure 1. Representation of the robot leader and the robot follower as material points

If some robot from the swarm is assigned as the leader, the stability of the swarm is at serious risk: in the case of a leader failure, the whole swarm becomes inoperable. To solve such a problem, we can identify a virtual leader and support a distance related to it [18]. The position of the virtual leader can be simply marked in the center of the swarm.

Method

The method presented here is designed to coordinate a swarm of robots to move towards a goal position while avoiding obstacles in their path. The swarm consists of a set of robots that move and update their velocity with some frequency. The velocity vector of the motion can be represented as a pair (v, w), where v is the linear velocity of the motion in meters per second, and w is the rotation angle.

The method takes as input the positions of the robots in the swarm, the position of the goal, and the range data obtained from the sensors of the observer robots from the previous step, as well as the velocity of the swarm from the previous step. The output of the method is the velocity vector that will be taken by the robots in the swarm in the next step.

The method can be described in the following four iterative steps:

Step 1: Calculation of the Position of the Virtual Leader. The position of the virtual leader is computed to determine the direction of motion of the swarm. The position of the virtual leader is determined based on the positions of the robots in the swarm and the position of the goal.

Step 2: Identification of Observer Robots. To sense obstacles in the path of the swarm, observer robots are selected. These observer robots have their rangefinder sensors turned on, while all other robots turn off their rangefinder to conserve power. Specifically, only three observer robots are needed: one in the center of the leading robot (the middle observer) and two others on either side (the left and right observers). The observer robots are identified based on their ability to sense obstacles in the path of the swarm, which is determined based on the positions of the robots in the swarm and the positions of obstacles.

Step 3: Processing the Data from Rangefinders. The left and right rangefinders of the observer robots are directed slightly to the side to avoid obstacles when changing direction. The data obtained from the rangefinders of the observer robots is processed to determine the distance to the nearest obstacle and its location relative to the swarm.

Step 4: Calculation of Velocity. The angular velocity of the swarm is determined based on the distance to the nearest obstacle as detected by the observer robots' rangefinders and the location of the goal position.

In summary, by following these iterative steps, our method is able to coordinate the movement of the swarm towards the goal while avoiding obstacles in its path. The method involves calculating the position of the virtual leader, identifying observer robots, processing the data from rangefinders, and calculating the velocity of the swarm. Each step takes input and produces output, as described above. The steps of the method are described in detail in subsequent chapters. A flowchart diagram of the method is shown in Fig. 2.

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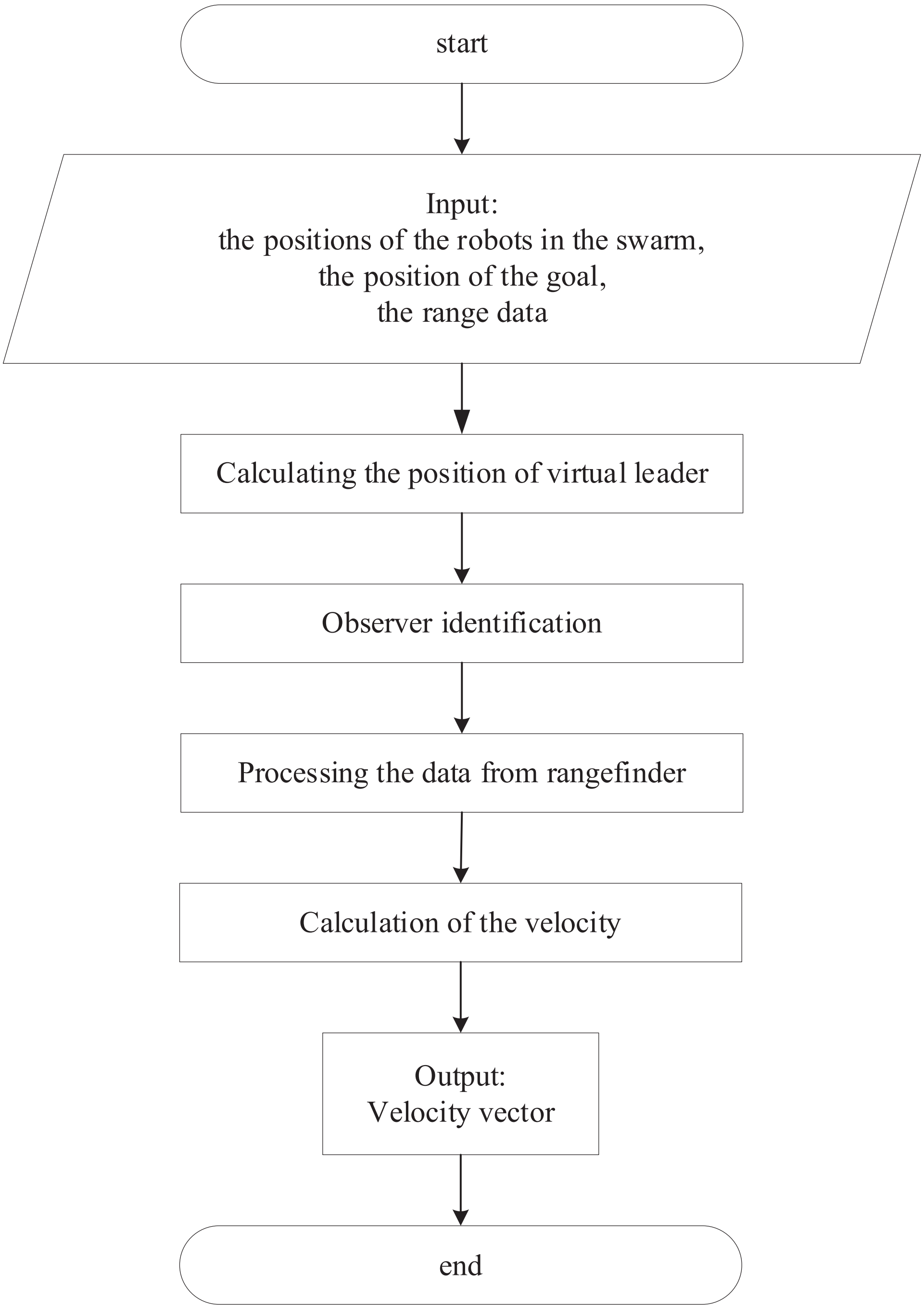

Figure 2. Flowchart of the method

Calculating the position of the virtual leader and identification of observers

The virtual leader's coordinates can be defined as the arithmetic average of the coordinates of the robots in the group.

If we shift the center of coordinates to the position of the virtual leader and rotate the X-axis in the direction of the swarm, we can easily identify the robot observers.

The position of any robot in this new system of coordinates is illustrated in Fig. 3. Here (x_i, y_i) is the position of ith robot, (x_L, y_L) is the position of the virtual leader, (x'_i, y'_i) is the coordinates of the ith robot in a new coordinate system.

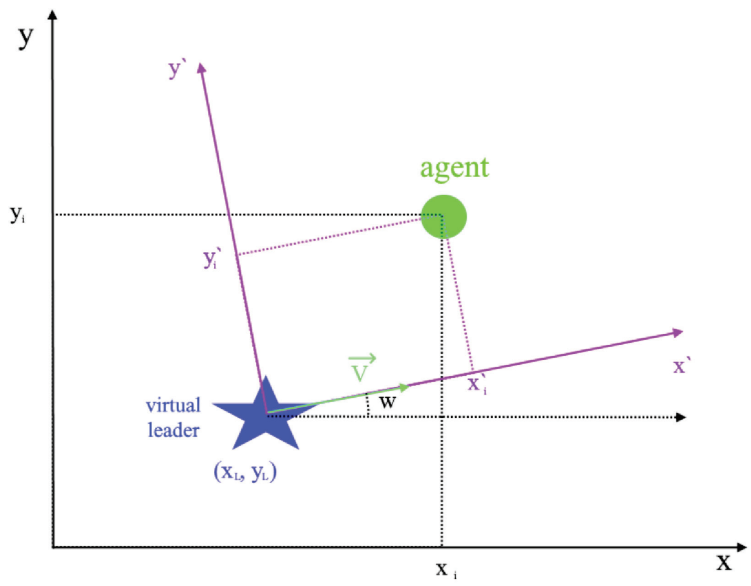

Figure 3. Switching to a new coordinate system centered on the virtual leader's position and directed by the swarm's movement

For example, the definition of observers is shown in Fig. 4. The central rangefinder is turned on at the robot that is ahead of all in the direction of motion, i.e., as the average observer, we choose the robot whose x' in the new coordinate system is maximum.

The left and right robot observers are defined similarly, the robots which are located at the maximum distance from the middle, i.e., from the x-axis, are chosen. The robot with the maximal value of y` includes the rangefinder on the left, and the robot with the minimal value of y` includes the rangefinder on the right.

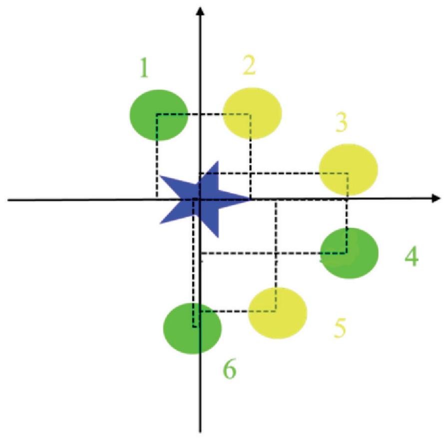

Figure 4. Selection of observers in a coordinate system centered on the virtual leader's position (the selected observers are shown in yellow)

In case there is only one agent left in the swarm (and everyone else is lost), it works as a middle observer. And if there are two robots left, they work as left and right observers.

Processing data from the rangefinder

The selected observers turn on their rangefinder and, depending on the information from their rangefinder, select the direction of movement straight, left or right. The angular velocity is calculated using the chosen direction.

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If the obstacles are detected only by the rangefinder on the left or on the left and in the center, the direction to the right is chosen. Similarly, if the right rangefinder or the middle and right rangefinder detects an obstacle, the left turn is selected.

If all rangefinder detects an obstacle or only the middle rangefinder detects it, then the swarm chooses the direction randomly, right or left; otherwise, it could collide head-on with an obstacle.

In the event that no rangefinder detects an obstacle, the direction towards the target is chosen.

Experimental analysis and discussion

In order to test the method, we developed a simulator in Python. The library PyGame was used to visualize the motion of the robots. The motion in the map with several obstacles was simulated. In the simulation, black indicates obstacles and red indicates the target point to which the swarm is moving. The robots are drawn in purple, and the observers turn green as the robots move.

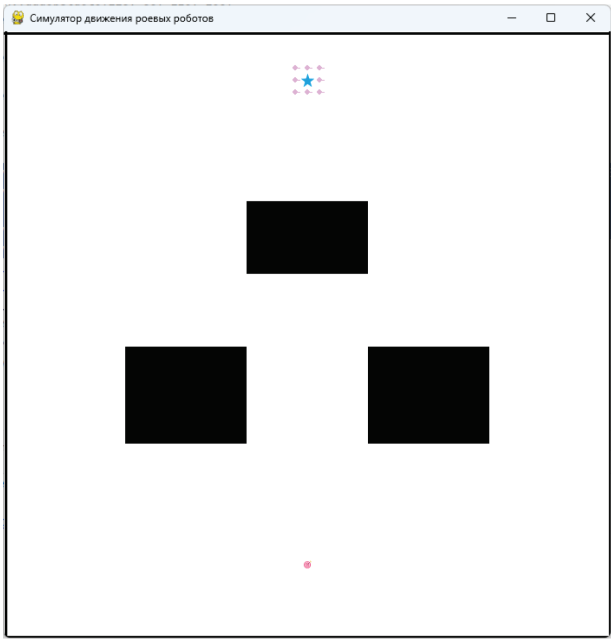

Figure 5. Initial state of the swarm in the map with a simple obstacle

The experimental study was conducted with values of linear velocity v and with values of the angle w by which the angular velocity changes. Changes in the number of steps to reach the target and the number of colliding agents in motion were tested. The values of linear velocity from 0.1 to 5 m/s with step 0.1 and values of angle w=1 degree, 3-degree, 5-degree, 15-degree, 30-degree, 45 degrees by which angular velocity is changed while moving were considered.

Obviously, the value of linear velocity greatly influences the number of steps to reach the goal. The greater the linear velocity, the faster the target position is reached.

The number of steps to reach the target is also influenced by the track of the swarm. Even by moving at a lower speed and choosing the most optimal path, it is possible to reach the target position faster.

At small values of the angle w=1-degree robots in a swarm get hit very frequently, and they reach the target position entirely only at small values of linear velocity.

In the values of linear velocity $v < 2$ m/s swarm reaches the target entirely; in the values of linear velocity in the range [2, 3) the number of collapsed robots is volatile, and in values greater than or equal to 3 m/s, all robots in the swarm are collapsed. The number of steps to reach the target decreases steadily with increasing linear velocity. Robots move in all values of linear velocity with similar tracks; in values of linear velocity greater than or equal to 3 m/s, the robots collide with the first obstacle without having managed to turn away.

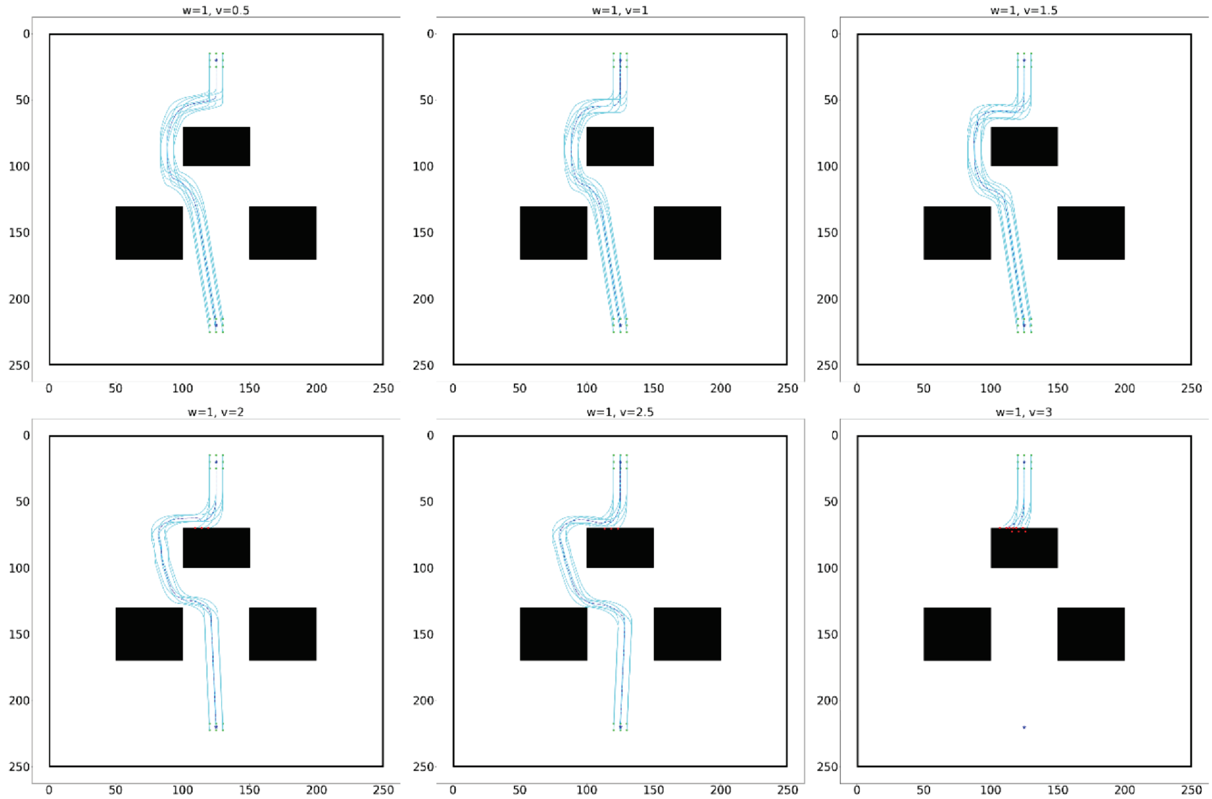

Figure 6. Swarm track at angle w=1 degree by which angular velocity changes and linear velocity v = 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s, 2.5 m/s, 3 m/s

When increasing the value of w to 2, 3, 5 degrees in general, the picture remains the same, but the swarm becomes more stable to losses and, with small values of linear velocity, more rapid in reaching the target. This is due to the fact that with increasing the value of w the swarm turns away from the obstacle faster and more quickly corrects its direction when bypassing the obstacle and crossing the gap.

Further increasing the value of w (up to 10, 15, 20, 30 degrees) makes the swarm more resistant to losses: if at $w = 10$ degrees the number of knocked down robots exceeds 3 only at high values of linear speed, then at 15, 20, 30 degrees it does not exceed 3 at all. Looking at this, we could conclude that at these values, the swarm becomes more flexible when moving, but here it leads to an increase in the number of robots knocked down. This is due to the fact that the robots begin to turn more sharply and are knocked down to the obstacles on the left or right side without having time to detect them.

At $w = 45$ degrees, the swarm starts to turn too sharply, so in many cases, the robots in the swarm cannot go around to the obstacles and eventually run into an obstacle either because of randomly correcting the rotation angle, or as mentioned above, not having enough time to detect an obstacle on the left or right side.

Conclusion

Group activity of mobile robots has a number of advantages, such as scalability, fault tolerance and the possibility for self-organization and self-regulation, which cannot be achieved with one central robot. To organize the action of robots in a group and to facilitate the group movement control, it is necessary to organize the movement by forming a certain geometrical figure of robots in the group - robot formation or graph of the system.

Movement in formation is widely used in practice. For example, groups of unmanned aircraft and unmanned submarines move to form a geometric structure for a military mission.

In this paper, a coordination and motion control method was presented that allows the group of robots to move while maintaining a geometric shape. The developed method for controlling the movement of swarm agents allows them to move toward a target without colliding with an obstacle while reducing the power consumption of rangefinders. It was proposed to turn on the rangefinder of only three observer robots. In order to coordinate the movements, the leader-follower method was used. A virtual leader was used to increase the fault tolerance of the swarm.

Also, in order to conduct an experimental study, the movements of the swarm consisting of nine robots were simulated. The number of robots knocked down and the number of steps to reach the target position were tested.

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