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Collaborative Hunting Strategy for Multi-Amphibious Spherical Robots in Obstacle Environments

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***Abstract*—Aiming at the problem of capturing dynamic targets in obstacle environment, this paper proposes the multi-robot collaborative hunting strategy based on artificial potential field, which can herd targets to a designated volume of space with a smaller number of robots required and lower computational cost. The strategy is composed of trajectory prediction of dynamic targets, resultant force generation mechanism based on artificial potential field, and cooperative path planning based on dynamic targets. In the proposed strategy, some obstacles in ideal positions can also be selected as defenders to form the hunting circle, which can reduce the number of robots required to complete the hunting task. In addition, robots near the target will actively drive the target to other robots to reduce the hunting time. The simulation results verified the effectiveness of the proposed multi-robot collaborative hunting strategy.**

***Index Terms*—-Multi-robot system, Collaborative hunting, Amphibious spherical robot, Obstacle avoidance.**

I. Introduction

In recent years, ocean engineering has attracted the attention of countries all over the world, and the demand for coastal exploration technology and equipment has also increased [1]–[3]. Compared with human exploration, amphibious robots are an effective solution to meet the exploration needs in complex amphibious environments. Compared with the traditional single robot exploration, the main advantage of multi-robot collaboration is that it does not rely on the high performance of a single robot in the system, and the failure of a single mobile robot will not cause the collapse of the entire system. Multi-robot cooperative hunting technology is one of the main application fields of multi-robot systems, which can be used in rescue and reconnaissance missions. Due to its important social significance, cooperative hunting technology has attracted the attention of researchers in the field of multi-robots in recent years.

Cooperative hunting control is one fundamental problem for multirobot systems, of which the objective is to design a control strategy that can help a group of pursuers cooperate with each other to capture another group of escapers. For the pursuers, the purpose is to catch the escapees in the shortest time; for the escapees, the purpose is to avoid being arrested within the specified time. It is obvious that the path planning for multiple robots is an essential problem in cooperative hunting control. In addition, collision avoidance should also be taken into consideration to guarantee the safety of the multirobot system. Paranjape *et al.* propose a herding algorithm suitable for a single unmanned robot, which enables a single robotic unmanned aerial vehicle to herd a flock of birds away from a designated volume of space [4]. Yu *et al.* proposed a dual bionic dolphin cooperative target tracking system [5]. The system uses an improved fast search tree path planning algorithm and a behavior-based cooperative tracking strategy to realize the two-line robot's tracking of the target. Aiming at the problem of harbour protection, Meng *et al.* proposed a multi-underwater robot cooperative hunting method based on prediction planning interception, which greatly reduced the hunting time by predicting the trajectory of the target [6]. Chipade *et al.* proposed a cooperative hunting strategy for herding a swarm of adversarial agents toward a safe area in a 2-D obstacle environment. The strategy does not need to know the state information of the attacker by letting the robot form a closed formation [7].

There are many phenomena of group behavior in nature, such as the migration of birds, the parade of fish, and the cooperative work of ant colonies. The behavior of individuals in these biological systems is spontaneous, but the entire system remains in a coordinated and orderly state. In recent years, many researchers have developed many classic swarm intelligence algorithms by studying the group behavior of natural organisms. By simulating the predatory behavior of humpback whales in the ocean, Mirjalili *et al.* proposed the whale optimization algorithm, which surrounds the prey through a bubble-net attacking method mechanism to complete the hunting task [8]. Kurdi *et al.* proposed a multi-robot cooperative hunting algorithm based on locust behavior for multi-UAV search and rescue tasks [9].Tang *et al.* proposed a strategy for tracking and searching dynamic targets for swarm robots with a consensus initiative mechanism [10]. This strategy utilizes residual pheromones in the environment to guide swarm robots, which reduces the requirement for robot capabilities. Although the swarm intelligent control algorithm has been studied for many years, its high computational cost makes it difficult to apply to small underwater robots.

At present, most studies on cooperative hunting strategies are based on ideal condition, such as environment without obstacles or target with constant speed. In addition, the number of robots required for hunting tasks is also an issue for small multi-robot systems. What's more, most cooperative hunting strategies are based on drones or land mobile robots. Compared with them, the computing power and maneuverability of underwater robots are limited due to the limitation of size and environmental conditions. Therefore, this paper proposes a multi-robot cooperative hunting strategy based on artificial potential field with less number of robots required and lower computational cost. The strategy is composed of trajectory prediction of dynamic targets, resultant force generation mechanism based on artificial potential field, and cooperative path planning based on dynamic programming. The resultant force generation mechanism based on the artificial potential field can herd the target to a designated volume of space. The cooperative path planning module gives the optimal path of each robot under the condition that the virtual resultant force generated by the multi-robot system is guaranteed to be stable.

The rest of this paper is organized as follows. Section II presents a brief introduction about our new generation multi-amphibious spherical robot system. The collaborative hunting strategy proposed in this paper is introduced in Section III. Simulations and results are provided in Section IV in order to assess the performance of the proposed approach. Section V provides a conclusion of the whole paper.

II. The Structure of Multi-Amphibious Spherical Robots

In this section, we will give a brief introduction to the experimental platform of the multi-amphibious spherical robot system and the sensors mounted on the robot.

Based on the robots mentioned in the paper [11]–[13], a multi-robot system based on a new generation of amphibious spherical robots with more perfect performance is designed. The composition of the amphibious spherical multi-robot system platform is shown in Fig.1, which includes a UAV module and two amphibious spherical robots. The UAV module is composed of an airborne computing module, a camera and a communication module, which mainly provides position information for the amphibious spherical robot. The amphibious spherical robot consists of a control module and a drive module. The motion controller and several sensors of the amphibious spherical robot, such as the control board NVIDIA Jetson TK1, inertial measurement unit (IMU) and binocular camera, are located in the control module of the upper part of the robot, which mainly helps the robot to perceive the surrounding environment and control robot movement. Four mechanical legs and four thrusters constitute the drive module of the amphibious spherical robot. When the robot is on land, the amphibious spherical robot can crawl like a turtle with the help of mechanical legs. When the robot is in water, the amphibious spherical robot can move like a submarine with the help of thrusters. The maximum speed of this amphibious robot in the water can reach 60 cm/s, and the maximum crawling speed of the robot on land is 6.05cm/s. The multiple amphibious spherical robot systems communicate with each other through a local area network (WLAN). The communication frequency between robots is 50Hz.

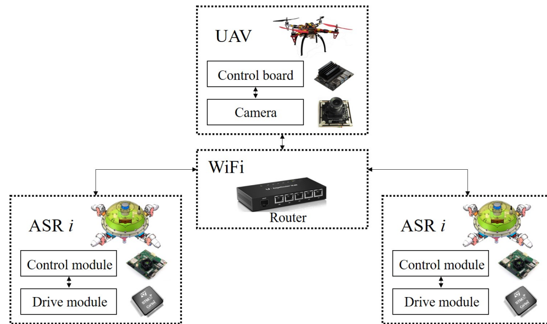


Fig. 1. The structure of proposed multi-amphibious spherical robots.

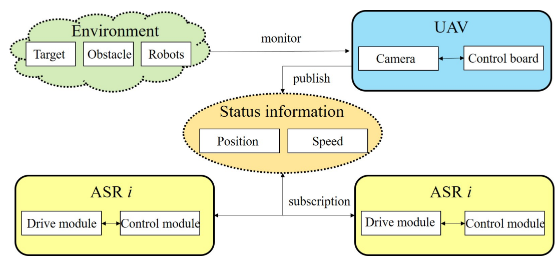


Fig. 2. Data flow between multiple amphibious spherical robots.

Fig.2 shows the schematic diagram of the data information flow of the multi-amphibious spherical robot system in the cooperative hunting task. The UAV gets the position of the obstacle and the target through the camera and publishes the information to other robots. Each amphibious spherical robot subscribes to this information to obtain the state of the environment for path planning and collision avoidance.

III. The Collaborative Hunting Strategy

In this section, a cooperative hunting control strategy for multi-amphibious spherical robot systems is proposed, which can help amphibious spherical robots to achieve efficient target capture in complex environments.

A. Problem Statement

Consider a multi-robot system of N_d robots and an attacker. In the multi-robot cooperative hunting strategy, the subscript d represents the defender, and the attacker is represented by the subscript a. We assume that the position and velocity of the i th robot are $p_{di}(t) = [x_{di}(t), y_{di}(t)]^T \in R^2$ and $v_{di}(t) = [u_{di}(t), w_{di}(t)]^T \in R^2$, respectively. Then the vector between the i th robot and the j th robot can be denoted by $r_{ij}(t) = p_{di}(t) - p_{dj}(t)$. We assume that all robots know the state of other robots and the attacker. The amphibious spherical robot in a 2D Euclidean space with single integrator dynamics given by

$$\dot{p}_{di}(t) = u_{di}(t) \tag{1}$$

where $u_{di}(t)$ is the control input of robot i.

The position and velocity of the attacker are denoted as $p_a(t) = [x_a(t), y_a(t)]^T \in R^2$ and $v_a(t) = [u_a(t), w_a(t)]^T \in R^2$, and assume that $\max(|v_a|) < \max(|v_d|)$. Then the vector between the ith robot and the intruder can be denoted by $r_{ai}(t) = p_a(t) - p_{di}(t)$. Let R_{agg} represent the perceived range of the attacker. The state of the attacker will be affected by the obstacles and the defender robot. Similar to the defender robot, the dynamics of the attacker can be described as a nonlinear, first-order differential equation

$$\dot{p}_a(t) = u_a(t) = H(r_{ai}(t)) \tag{2}$$

where H denotes the attacker response to the obstacles or the defender, which is design based on artificial potential field

$$H(r_{ai}(t)) = \begin{cases} \eta(1 - \dfrac{R_{agg}^3}{|r_{ai}(t)|^3})r_{ai}(t), |r_{ai}(t)| < R_{agg} \\ 0, |r_{ai}(t)| >= R_{agg} \end{cases} \tag{3}$$

When the distance $|r_{ai}(t)|$ between the attacker and defender decreases, $H(r_{ai}(t))$ approaches infinity, which can make the robot avoid collisions.

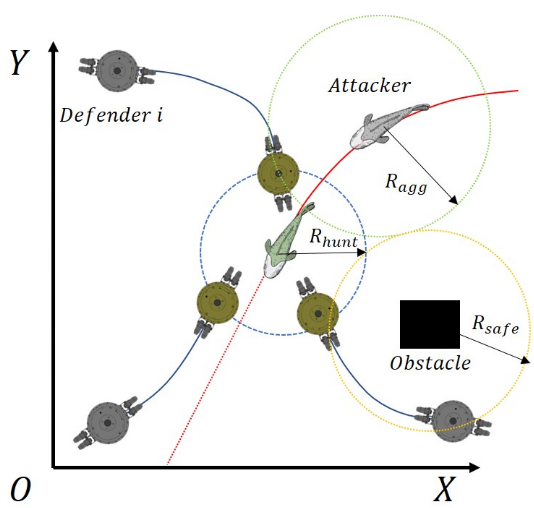


Fig. 3. Example of cooperative hunting of multiple amphibious spherical robots in obstacle environment.

In order to achieve dynamic target capture in complex environments, the amphibious spherical robot needs to cooperate with each robot and make effective use of surrounding obstacles. A cooperative hunting example with the randomly distributed ASRs is depicted as shown in Fig.3. Although the proposed cooperative hunting control strategy is suitable for multi-robot systems, the number of hunting robots can be reduced by utilizing obstacles in complex environments to form the hunting circle. The red dotted line in Fig.3 is the predicted movement trajectory of the target, which is calculated by the trajectory prediction module. The trajectory prediction module is part of a collaborative hunting strategy. It can help the robot to forecast the intersection point in advance and plan the path to this point directly. During the process of the multi-robot cooperative hunting, the robot closer to the target will drive the target to other robots to reduce the hunting time. In addition, compared with the traditional hunting strategy using only robots, the proposed hunting strategy allows robots and obstacles to form a hunting circle, which has a higher hunting efficiency.

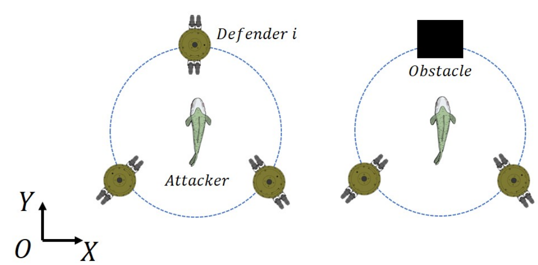


Fig. 4. Conditions for the successful collaborative hunting.

When the target is surrounded by several amphibious spherical robots or obstacles at the same time, the hunting task is completed. During the process of collaborative hunting, it takes at least three defenders to surround an attacker. In the proposed collaborative hunting strategy, the defender can be a robot or an obstacle. By using obstacles to form the hunting circle, the number of defender robots can be effectively reduced. Fig.4 shows two examples of a successful hunting. The attacker is located at the center of the circle formed by the robot or obstacle, and the radius is less than R_{hunt}, which can be expressed as

$$p_a(t) = \frac{1}{N_d} \sum_{i=1}^{N_d} p_{di}(t) \tag{4}$$

$$|r_{ai}(t)| = |p_a(t) - p_{di}(t)| <= R_{hunt} \tag{5}$$

B. Approaching Stage

In the defender approaching the attacker phase ($|r_{ai}(t)| >= R_{agg}$), the defender's controller aims to approach the obstacle in the shortest time while avoiding the obstacle. The defender's control law in the proposed control strategy consists of two parts: trajectory prediction and obstacle avoidance. Trajectory prediction ensures that the defender approaches the attacker in the shortest time by predicting the movement trajectory of the attacker, while the obstacle avoidance algorithm allows the defender to approach the attacker while avoiding obstacles. The defender's control law is designed as

$$u_{di}(t) = \omega(p_{di}(t) - p'_{di}(t)) + (1-\omega)\sum_{i=1}^{N_o} H(r_{io}(t)) \quad (6)$$

where ω is the weight; $p'_{di}(t) = [x_{ai}(t), y_{ai}(t)]^T$ is the intersection of the attacker and defender trajectories, which is the path point where the encounter time between the attacker and the defender takes the shortest time; H denotes the defender response to the obstacles or the defender, which is design based on artificial potential field, which can also can be obtained by equation (3).

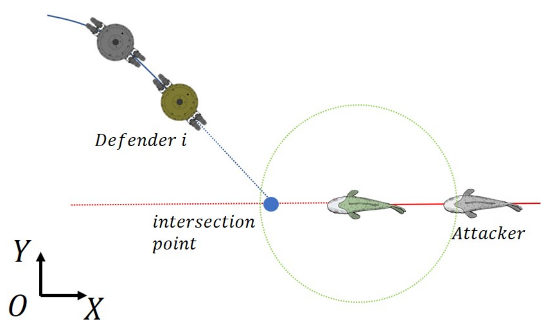


Fig. 5. The principle of trajectory prediction.

The principle of trajectory prediction is shown in Fig.5 During the trajectory prediction process of the attacker, the velocity of the attacker is assumed to be constant. Once the speed of the attacker changes, the trajectory prediction module will re-predict the movement trajectory of the attacker. Then, the function should satisfy the following two conditions

$$\frac{y_a(t) - y_a(t-1)}{x_a(t) - x_a(t-1)} = \frac{y_{ai}(t) - y_a(t)}{x_{ai}(t) - x_a(t)} \quad (7)$$

$$\frac{|p'_{di}(t) - p_a(t)|}{v_a(t)} = \frac{|p'_{di}(t) - p_{di}(t)|}{v_{di}(t)} \quad (8)$$

C. Capture Stage

In the capture phase ($|r_{ai}(t)| < R_{agg}$), inspired by the motion of the amphibious spherical robot, a cooperative hunting strategy based on artificial potential field is proposed. The main idea of it is shown in Fig.6. In the motion control of the amphibious spherical robot, the four mechanical legs generate the desired resultant force by changing the angle and thrust of the thrusters to push the body of the robot to the specified position. Similar to the principle of underwater motion of amphibious spherical robots, each defender robot in the hunting process is equivalent to the mechanical leg of the amphibious spherical robot, and the attacker is equivalent to the body of the amphibious spherical robot. In order to generate the desired resultant force, the defender robot can change the resultant force received by the attacker by changing the relative position of the defender and the attacker. Based on an artificial potential field, the resultant force received by the attacker can be described as

$$u_{di}(t) = k_d\sum_{i=1}^{N_d} H(r_{ai}(t)) + k_o\sum_{i=1}^{N_o} H(r_{aio}(t)) \quad (9)$$

where k_o and k_d are the weight; N_o and r_{aio} denote he number of obstacles and the vector between the obstacles and the attacker.

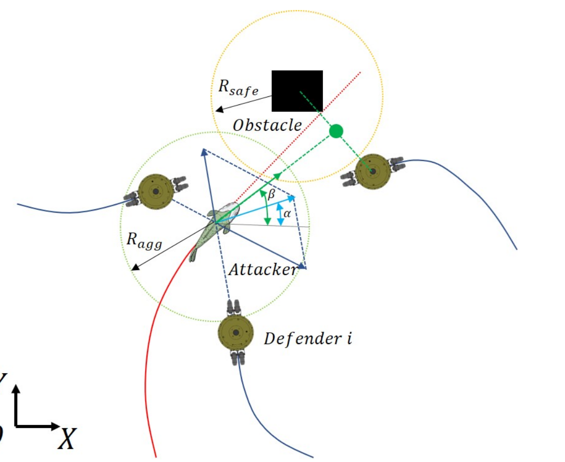


Fig. 6. The generation mechanism of resultant force based on artificial potential field.

When multiple robots capture attackers in a real environment, the situation is often more complicated, such as the blocking of obstacles in the environment and the failure of some defender robots. In addition, at least 3 or more robots are required to complete the hunting task, which is an impossible task for a multi-robot system with a small number of robots. In order to solve the above problems, a herding strategy based on the repulsion field is designed in the proposed cooperative hunting strategy, and the obstacle is regarded as a stationary robot in the hunting process to complete the hunting task with a smaller number of robots. The principle of "herd" is shown in the Fig.6. In order to complete a cooperative hunting task in limited time with a smaller number of defender robot, the defender's controller needs to be designed to help defender robots drive attackers to areas of other defender or obstacles that constitute a hunting circle. Therefore, the resultant force generated by the roundup robot should satisfy the following conditions

$$\tan_\alpha = \frac{y_k(t) - y_a(t)}{x_k(t) - x_a(t)} \quad (10)$$

where

$$p_{di}(t) = \frac{1}{2}\sum_{i=1}^{N_d} p_{di}(t) + \frac{1}{2}\sum_{i=1}^{N_o} p_o(t) \tag{11}$$

In the previous chapters, the principle of resultant force and the generation of expected resultant force have been introduced. Here, a general formulation of the problem is presented so that the optimisation of the objective function corresponds to the optimal pose of the multi-robot team with respect to the resultant force while ensuring that the system can avoid obstacles. In the multi-robot cooperative hunting process, the parameter that can be adjusted in the system is the position of each defender robot. Therefore, for a multi-robot system with N_d robots, the number of scalars that need to be optimized is $2N_d$. In order to minimize the error between the resultant force generated by the multi-robot system and the expected resultant force, the objective function to be minimized is designed as

$$e(t) = |u_a'(t) - u_a(t)| \tag{12}$$

When the objective equation is at the minimum value, the resultant force generated by the multi-robot system is consistent with the expected resultant force. The limitations of this problem are then defined by the physical limitations of the system and ensuring the immunity of the system. These are expressed as

$$|p_{di}(t+T) - p_{di}(t)| <= r_d \tag{13}$$

$$|r_{ai}(t)| = |r_{aj}(t)|, i, j \in N_d \tag{14}$$

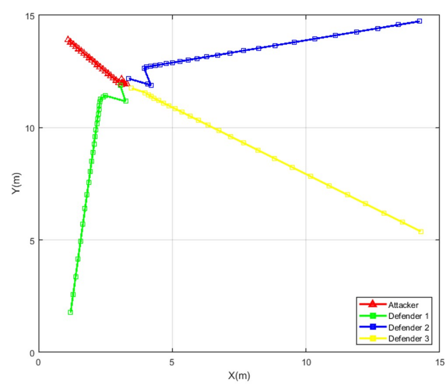
$$|p_{di}(t+T) - p_o(t)| > R_{safe} \tag{15}$$

Equation (13) is the physical constraint condition of the multi-robot system. During the sampling time T, the maximum distance the robot can move is r_d. When a multi-robot system generates expectations and moments, the position of each robot should be guaranteed to be symmetrical to effectively resist external disturbances. This requirement is formulated in equation (14). Equation (15) ensures that the robot is compatible with other robots or obstacles The distance between objects is greater than the safety distance to avoid collision.

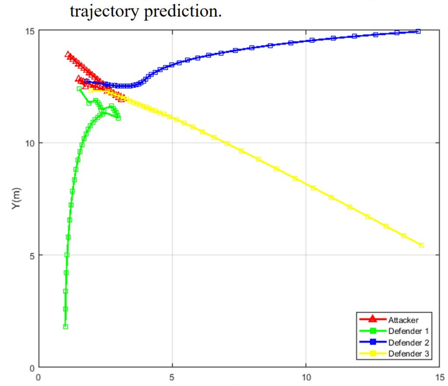
IV. Simulation and Results

In this section, the proposed collaborative hunting control strategy for the multi-amphibious spherical robot is verified by simulation.

In the first simulation, the three defenders were required to capture the attacker in an open area. The attacker's initial coordinates were $[1, 14]^T$. When there were no defenders near the attacker, the attacker would move at a speed of $[0.2, -0.2]^T$. The initial coordinates of the defender are $[1, 1]^T$, $[15, 15]^T$ and, $[15, 5]^T$. We assume that the attacker's maximum speed is 0.03m/s and the defender's maximum speed is 0.08m/s. The attacker's perception radius is set to 1m. The condition R_{hunt} for the success of the hunting is set as 0.5m.When the distance between the defender and the attacker is less than the perception radius, the attacker's state will change. Fig.7(a) shows the trajectories of several defenders and that of the attacker. The final hunting radius R_{hunt} is 0.25m. The data clearly shows the attacker being deflected away from their original flight path as it approaches the defenders. After the attacker's original flight path is changed, three defenders also adjusted their trajectories to keep the attackers in the hunting circle. Comparative experiments without trajectory prediction are also shown in Fig.7(b). The total path lengths of each robot in Fig.7(a) are 10.61m, 11.46m and 12.82m , respectively, while the total path lengths of each robot in Fig.7(b) are 11.73m, 12.93m and 14.43m, respectively. From the results, the proposed multi-robot round-up strategy effectively reduces the distance and time consumption of each defense robot.



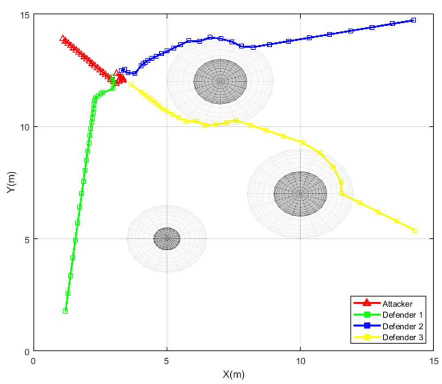
(a) The trajectories of multi-robot hunting with trajectory prediction.



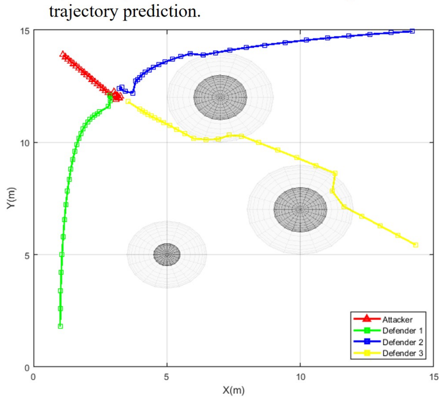
(b) The trajectories of multi-robot hunting without trajectory prediction.

Fig. 7. Performance of the the proposed collaborative hunting strategy in open area.

In the second simulation, three defenders are required to capture the attacker in an obstacle environment. The initial position and velocity of each robot are the same as in the first simulation experiment. Three sphere obstacles are considered with centers at $[10,7]^T$, $[5,5]^T$ and $[7,12]^T$ and the radius of 1m, 0.5m and 1m. The drag coefficient η and the protective distance in the artificial potential field are set to 1 and 1m, respectively. Fig.8(a) shows the paths of the defenders and the attacker after the enclosing and herding phases are completed. The final hunting radius R_{hunt} is 0.41m. From the Fig.8(a), the defenders are able to capture the attacker while avoiding collisions. Comparative experiments without trajectory prediction are also shown in Fig.8(b). The total path lengths of each robot in Fig.8(a) are 10.75m, 11.57m and 13.58m, respectively, while the total path lengths of each robot in Fig.8(b) are 10.66m, 11.64m and 13.74m, respectively. Under the influence of obstacles, the proposed cooperative hunting strategy still reduces the distance and time consumption of some defender robots.



(a) The trajectories of multi-robot hunting with trajectory prediction.



(b) The trajectories of multi-robot hunting without trajectory prediction.

Fig. 8. Performance of the the proposed collaborative hunting strategy in obstacle environment.

V. Conclusions

In this paper, a cooperative hunting control strategy for multi-amphibious spherical robots is proposed in the obstacle environment. Aiming at the problem of dynamic target, the proposed control strategy enables the defender robot to forecast the intercept point and hunt the moving attacker efficiently. Furthermore, compared with the traditional hunting strategy, the proposed strategy designs a herding-like hunting strategy, which utilizes an artificial potential field to herd attackers to a designated volume of space. In this way, the distance of all robots is shortened, and the time to complete the hunting task is further reduced. Finally, the simulation results verified the effectiveness of the proposed multi-robot collaborative hunting strategy.

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References

[1] R. An, S. Guo, Y. Yu, C. Li, and T. Awa, "Task planning and collaboration of jellyfish-inspired multiple spherical underwater robots," *Journal of Bionic Engineering*, pp. 1–14, 2022.

[2] R. An, S. Guo, L. Zheng, H. Hirata, and S. Gu, "Uncertain moving obstacles avoiding method in 3d arbitrary path planning for a spherical underwater robot," *Robotics and Autonomous Systems*, p. 104011, 2022.

[3] H. Yin, S. Guo, and M. Liu, "A virtual linkage-based dual event-triggered formation control strategy for multiple amphibious spherical robots in constrained space with limited communication," *IEEE Sensors Journal*, pp. 1–1, 2022.

[4] A. A. Paranjape, S.-J. Chung, K. Kim, and D. H. Shim, "Robotic herding of a flock of birds using an unmanned aerial vehicle," *IEEE Transactions on Robotics*, vol. 34, no. 4, pp. 901–915, 2018.

[5] J. Liu, Z. Wu, J. Yu, and Z. Xue, "Cooperative target tracking in aquatic environment using dual robotic dolphins," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. PP, no. 99, pp. 1–11, 2019.

[6] X. Meng, B. Sun, and D. Zhu, "Harbour protection: moving invasion target interception for multi-auv based on prediction planning interception method," *Ocean Engineering*, vol. 219, p. 108268, 2021.

[7] V. S. Chipade and D. Panagou, "Multiagent planning and control for swarm herding in 2-d obstacle environments under bounded inputs," *IEEE Transactions on Robotics*, vol. 37, no. 6, pp. 1956–1972, 2021.

[8] S. Mirjalili and A. Lewis, "The whale optimization algorithm," *Advances in engineering software*, vol. 95, pp. 51–67, 2016.

[9] H. Kurdi, S. Al-Megren, E. Aloboud, A. A. Alnuaim, H. Alomair, R. Alothman, A. B. Muhayya, N. Alharbi, M. Alenzi, and K. Youcef-Toumi, "Bee-inspired task allocation algorithm for multi-uav search and rescue missions," *International Journal of Bio-Inspired Computation*, vol. 16, no. 4, pp. 252–263, 2020.

[10] Q. Tang, Z. Xu, F. Yu, Z. Zhang, and J. Zhang, "Dynamic target searching and tracking with swarm robots based on stigmergy mechanism," *Robotics and Autonomous Systems*, vol. 120, p. 103251, 2019.

[11] H. Xing, Y. Liu, S. Guo, L. Shi, X. Hou, W. Liu, and Y. Zhao, "A multi-sensor fusion self-localization system of a miniature underwater robot in structured and gps-denied environments," *IEEE Sensors Journal*, vol. 21, no. 23, pp. 27136–27146, 2021.

[12] H. Xing, L. Shi, H. Xihuan, Y. Liu, Y. Hu, D. Xia, Z. Li, and S. Guo, "Design, modeling and control of a miniature bio-inspired amphibious spherical robot," *Mechatronics*, vol. 77, p. 102574, 05 2021.

[13] X. Hou, S. Guo, L. Shi, H. Xing, and D. Xia, "Improved model predictive-based underwater trajectory tracking control for the biomimetic spherical robot under constraints," *Applied Sciences*, vol. 10, no. 22, p. 8106, 2020.