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Multiple Robotic Fish's Target Search and Cooperative Hunting Strategies

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Abstract

Multi-robotic fish's cooperative hunting is through that the robotic fish groups' collaboration and against, ultimately achieves the purpose of encirclement target; there is important significance to realize security of the underwater group. This paper studied the problem of multi-robotic fish's target search and cooperative hunting, discussed on the multi-robotic fish's group size, conditions of search target and hunting successful, conditions of failure successfully. Proposed the partition global search strategy, hunt-robotic fish use a hunting strategy that based on dynamic surrounding point, and designed intelligent escape strategy for invasion-robotic fish. A simulation experience is conducted to verify the hunting strategy and escape strategy that proposed in this paper, and the results show that on the basic of fast search to the target, multi-robotic fishes can achieve hunting task efficiently, but also reflects the game against behavior between the intruders and hunters.

Keywords: *multi-robotic fishes; target research; co-operative hunting; surrounding point; escape strategy*

1. Introduction

The problem of Multi-underwater robot's cooperative hunting originated from marine predator group capture the prey behavior [1], that is refer to, through the mutual cooperation between the multiple underwater robots to complete the task of capturing the moving target, and for the realization of the underwater group security (such as capture of the invaders, security patrols) has very important significance [2] [3]. At present, the land robot's cooperative hunting has made many achievements, such as [4] classification of the current state by using the proximity rule, for each state using a genetic algorithm to search, to achieve the optimal action of hunt-robot; Ref. [5] using the Grid method to study of the multi-robot hunting dynamic target strategy, proposed the concept of the virtual range and reduced the number of dynamic programming.

Based on the inspiration of land robot's cooperative hunting algorithm, this paper take the robotic fish[6] as the research object, proposed target search strategy and cooperative hunting strategy of the multi-robotic fishes, in the premise of the robotic fish successful search goals, hunt-robotic fishes using cooperative hunting algorithm based on "dynamic rounded point" to achieve encircled the target. When the invasion-robotic fish found their safety is threatened, they immediately escape by using intelligent adjustment escape direction and velocity behavior, which in order to increase the difficulty of the capture task.

2. Problem Description

In the two-dimensional (xoz) finite simulation environment, the simulation environment of the initial state, randomly distribution of n hunt-robotic fishes $H=\{H_1, H_2,..., H_n\}$ ($n \geq 3$), speed is V_h; m invasion-robotic fishes $I=\{I_1,I_2,...,I_m\}$ ($m \geq 1$), speed is V_I, and the destination of invasion-robotic fish is area G. When both the invasion-robotic fish and the hunt-robotic fish have searched to each other in the system, they use the escape strategy or hunting strategy to game of competition and cooperation. We will do the following assumption:

(1) *Basic information:* hunt-robotic fish and invasion-robotic fish with the same perception, information of position and direction (x,z,θ) can be perceived to each robotic fish, where

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(x,z) is coordinate, θ is the robotic fish's body direction; detection range of robotic fish is a fan-shaped area with detection distance r and horizontal open angle Φ;

(2) The velocity relationship of invasion-robotic fish and hunt-robotic fish is: $V_I=V_h+\lambda$ ($\lambda \in z$), and the velocity of invasion-robotic fish shall not be less than the hunt-robotic fish in the stage of hunting;

(3) Conditions of Hunting successfully: hunt-robotic fish formed an circle taking the invasion-robotic fish as the centre, radius less than or equal to R, and the formation angle of any two adjacent robotic fish is: $\theta(H_i, H_j) = 2\pi/n \pm \Delta\varepsilon \quad (0^\circ \le \Delta\varepsilon \le 15^\circ)$;or when the distance from invasion-robotic fish to the boundary of field D ≤ R, and there are n-1 hunt-robotic fishes with the border together formed an circle taking invasion-robotic fish as the centre, radius less than or equal to R;

(4) Hunting task failure: if the invasion-robotic fish arrived in the target area G successfully or fled back to the safety zone.

3. Multi-Robotic Fish's Partition Global search Algorithm

Target search [7] strategy is the strategy that adopted by all robotic fishes in randomly dispersed state, target search is the premise of completing the task, hunting would not be implemented until found the intruders, only when found out the intruders would implementation of hunting, while the search algorithm should ensure that as soon as possible to find out intrusion-robotic fish.

Definition 1 the ratio of search coverage C: C is refers to the moment of t, the ratio of the sum of detection range area of hunt-robotic fish and with the area of entire search region Areafield (except the overlap region); where Areai is detection range of robotic fish, r is detection distance, and Φ is horizontal open angle of direction perceived, formula of C is expressed as in Eq. (1):

$$\begin{cases} Area_{sum} = \sum_{i=1}^{n} Area_i (Area_i = \frac{1}{2}\phi \cdot r^2) \\ C = (Area_{sum} - Area_{overlap}) / Area_{field} \end{cases} \tag{1}$$

Definition 2 safety area: Initial distribution area of invasion-robotic fish, in which hunt-robotic fish are not visible to the invasion-robotic fish;

Definition 3 target area: refer to the area of invasion-robotic fish want to damaged;

In order to improve ratio of the search range coverage and reduce the probability of repeat search, taking into account as much as possible to reduce the risk of collision between the robotic fishes, this paper proposed an algorithm of partition global search, make the hunt-robotic fish distributed evenly throughout the whole area. The search algorithm is described as follows:

Step 1: According to the size of hunting environment, divided it into safety area where the intrusion-robotic fish initial location and search area where the hunt-robotic fish initial location;

Step 2: In order to meet the high ratio of coverage and overlap area is small, so divided the search area into four sub-areas averagely, each sub-region using the principle of "nearest neighbor" select n/4 hunt-robotic fish to search invaders, as shown in Figure1;

Step 3: Hunt-robotic fish search targets in its area of responsibility by random walking;

Step 4: When the invasion-robotic fish get into the detection range of hunt-robotic fish, namely, r≤1500mm and their body direction's angle $\theta(I, H_i)$ meet the condition of $-360/n^\circ \le |\theta_H| - |\theta_I| \le 360^\circ / n$, it indicates that the hunt-robotic fish found the target, called the Cooperative Hunting algorithm based on "dynamics surrounding point", otherwise go to step3;

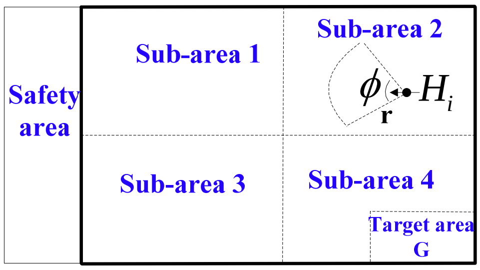

Figure 1. Schematic diagram of partition global search algorithm

4. Based on "Dynamic Surrounding Point" of the Design and Implementation of Cooperative Hunting

4.1. Based on "Dynamic Surrounding Point" Cooperative Hunting Design

In the process of hunting, when the invasion-robotic fish have perceived there is hunt-robotic fish in around, it will select intelligent escape behavior, then hunt-robotic fish need to hunting in the competition mode of the target continuous escape, in order to improve the efficiency of hunting, this paper using “dynamic surrounding point” formed surrounded algorithm to hunting the invasion-robotic fish. First, make the following definition:

Definition 1 Leader role: In the process of partition search, the robotic fish that firstly have searched intruder set to leader, it will responsible for the distribution of tasks to other members;

Definition 2 Ring of encirclement: hunt-robotic fish formed a circle taking the invasion-robotic fish as the centre, radius is R’, and hunt-robotic fish distributed in the circle as evenly as possible;

Definition 3 Surrounding point: ideal position of each hunt-robotic fish on the ring of encirclement;

Definition 4 Capture point: capture position of hunt-robotic fish when hunting invasion-robotic fish successfully.

In the process of multi-robotic fishes Cooperative Hunting, in the premise of fast search to the intruder, leader predict the intruder’s position of the next moment, and allocated surrounding points to other hunt-robotic fishes, then they move to the expectation surrounding point quickly. However, if surrounding point of a robotic fish Hi falling into obstacles environment or falling into the boundary of field, Hi will abandon the expectation surrounding point, directly move to the intruder’s direction and tracking intruders in real-time, Hi will return to the predetermined surrounding point until the blind state is released. During the process of moving to the intruder, hunt-robotic fishes shrink the ring of encirclement radius by dynamic adjustment Leader role, hunting task success until each hunt-robotic has reached the capture point, otherwise hunting failure.

4.2. Based on "Dynamic Surrounding Point" Cooperative Hunting Algorithm Implementation

The flow chart of based on "dynamic surrounding point" cooperative hunting algorithm is shown in Figure 2. Where, the implement methods of the main module as follow.

1. Predict the centre position of the ring of encirclement

Leader predicted invader’s position of the next moment according to its current position and direction (x_I,z_I,θ_I); if invasion-robotic fish moving with velocity V_I, and turned ξ angles after Δt times, then its instantaneous position satisfy the Eq. (2) after Δt times:

$$\begin{cases} x_{nI} = V_I \cdot \Delta t \cdot \cos(\theta_I + \xi) + x_I \\ z_{nI} = V_I \cdot \Delta t \cdot \sin(\theta_I + \xi) + z_I \end{cases} \quad (2)$$

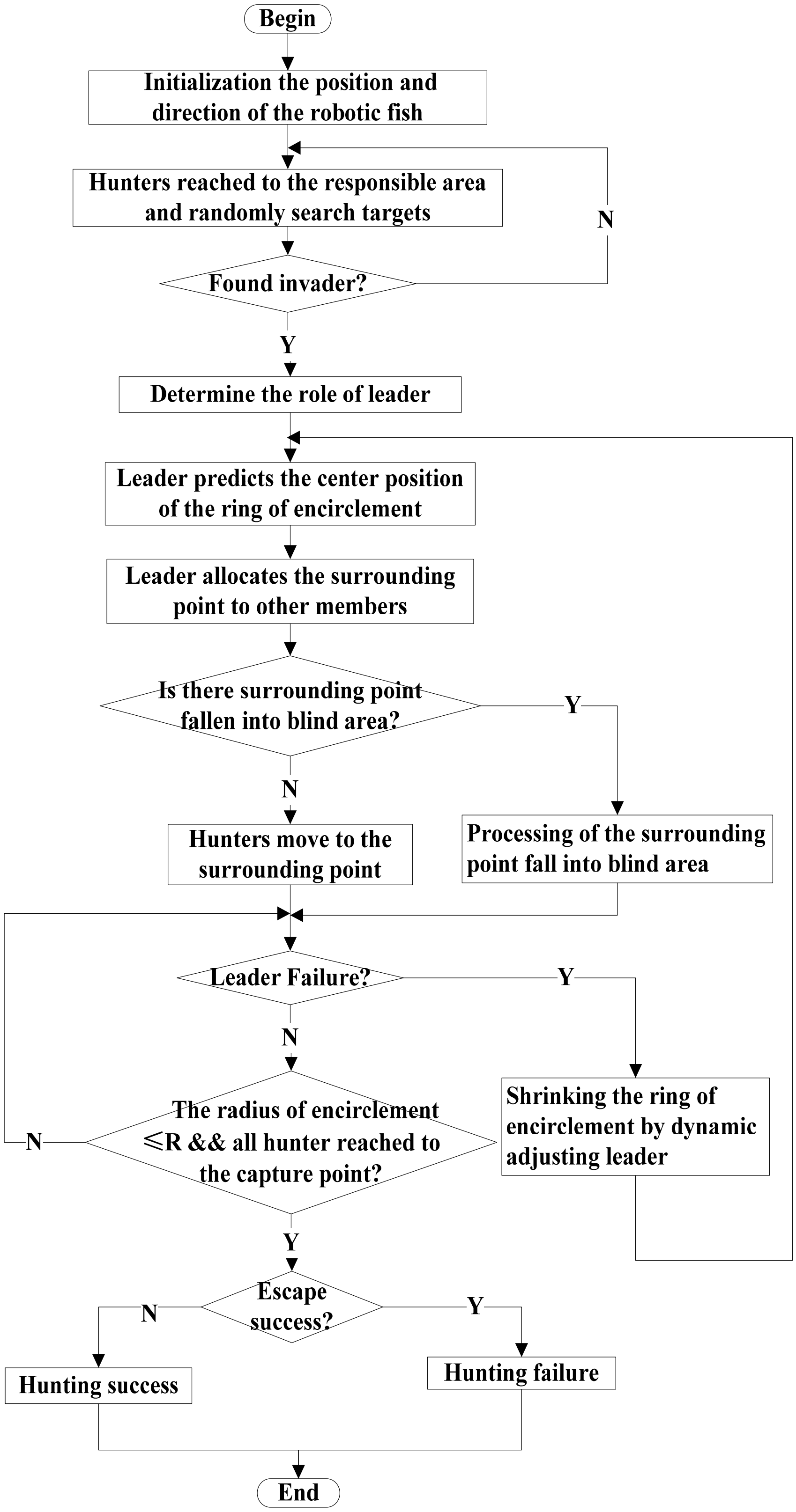

Figure 2. Algorithm of multiple robotic fish cooperative hunting flow chat

2. Allocation of the Surrounding point

According to the position and direction information that predicted, and the relationship of position between each hunt-robotic fish, following the principle of evenly allocation, Leader establishes surrounding point in around of intrusion-robotic fish. After receiving the tasks that leader has assigned, hunt-robotic fishes move to each surrounding point, formed a ring of encirclement that taking the invasion-robotic fish's position as the centre, radius is R', and ready to round up. Main task of leader is planning the surrounding point that around the invasion-robotic fish for all hunt-robotic fishes, the allocation method is shown in Figure 3:

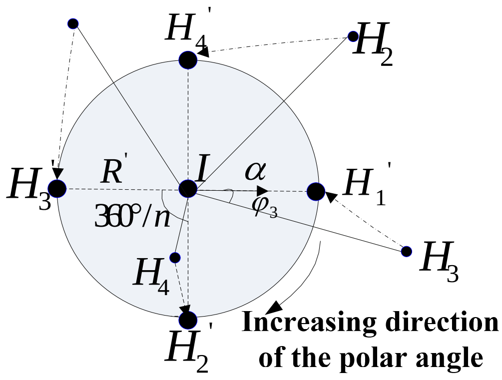

Figure 3. Diagram of surrounding point allocation

Where, H_i represents the hunt-robotic fish, and $H_i^{'}(x_i^{'}, z_i^{'})(i \le n)$ is surrounding point that around intrusion-robotic fish I, the angle between adjacent two surrounding points is β=360°/n, α is current movement direction of the intrusion-robotic fish, the coordinates of each surrounding point can be obtained by Eq. (3):

$$\begin{cases} x_i^{'} = x_{nI} \pm R^{'} \times \cos(\alpha + i\beta) \\ z_i^{'} = z_{nI} \pm R^{'} \times \sin(\alpha + i\beta) \end{cases} \tag{3}$$

Take the "+" sign when the position of surrounding point in the positive direction of the global coordinate system, otherwise take "-" sign. We can see from Figure 2, $H_1'(x_1', z_1')$ is the surrounding point that located in the motion direction of invasion-robotic fish, so established polar coordinate system with pole I, and pole axis IH_1, and point H_1,H_2,H_3,H_4 fall in the polar coordinate plane, calculate all the hunt-robotic fish's current position of the polar angle $\varphi_1,\varphi_2,\varphi_3,\varphi_4$ (in Figure 3, such as taking H_3 as an example, its polar angle is φ_3), setting the clockwise direction as the increasing direction of polar angle, so the polar angle order from small to large is $\varphi_i=\{\varphi_3,\varphi_4,\varphi_1,\varphi_2\}$, φ_i correspond to the hunt-robotic fish is $H_i=\{H_3,H_4,H_1,H_2\}$, and φ_i correspond to the surrounding point set is $H_i^{'}=\{H_1^{'},H_2^{'},H_3^{'},H_4^{'}\}$, by sequentially matching elements of the set of H_i with $H_i^{'}$, can obtain the surrounding point that hunt-robotic fish to be reached in the hunting process. From Figure 3, we can see the matching results that the direction of dotted line, the distance from hunt-robotic fishes to their expectation surrounding point is closer and collision avoidance.

3. Processing of the surrounding point fall into blind area

In the process of hunting, the following two situations will cause the surrounding point fall into the blind area, thus resulting in the hunt-robotic fish can't reach to the specified surrounding point to finish capturing task:

Situation one: because of that there may be obstacles in the hunting environment, the surrounding point that leader allocated for each hunt-robotic fish would be occupied by obstacles, or there may be obstacles that between the invasion-robotic fish and surrounding points. In Figure 4, H_1's surrounding point H3' fallen into barriers, and there is obstacle between H_2 and the surrounding point H_1';

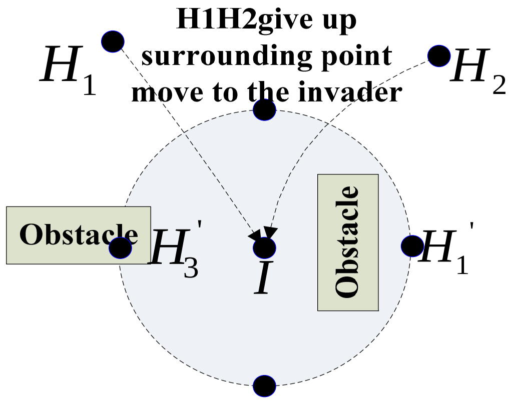

Figure 4. Surrounding point fallen into the barriers

Situation two: in the bounded environment of two-dimensional, surrounding point fall into outside of the boundary. In Figure 5, H_4's surrounding point H_2' fallen into outside of the boundary;

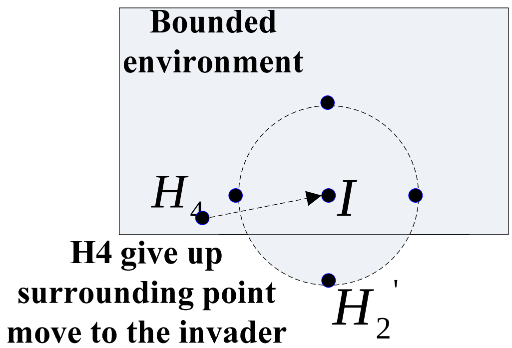

Figure 5. Surrounding point fallen outside the border

Processing method: due to both the obstacles and boundary of field have the auxiliary function of hunting, so the robotic fishes H_1H_2 that surrounding point fallen into the barriers view obstacles as for their surrounding points, the robotic fish H_4 that surrounding point fallen outside the boundary view the boundary as for its surrounding point, and robotic fishes $H_1H_2H_4$ move to the direction of invasion-robotic fish. When surrounding points H_3'H_1'H_2' released the blind area, robotic fishes $H_1H_2H_4$ will back into the hunting task.

4. Shrinking the ring of encirclement by dynamic adjusting leader

If the current leader encounter obstacles or exception occurs, then leader failure and re-select leader to ensure the movement of system as a whole. The principle of select new leader: judging the distance D between the invasion-robotic fish and hunt-robotic fish's current position, take the robotic fish that meet the condition of D=min $\{\| H_i(x_i, z_i) - H_i^{'}(x_i^{'}, z_i^{'}) \|\}$ as for the new leader.

The new leader will diminish the radius R' of the ring of encirclement, take the current position of invader as the center, and re-allocate the surrounding point for other hunt-robotic fishes in accordance with the rule of A, in order to ensure that the invasion-robotic fish always on the ring of encirclement.

5. Intelligent Escape Strategy of Intrusion-Robotic Fish

The escape strategy of invasion-robotic fish determines the difficulty of the hunting task[8], and meantime it is also a important factor to measure the effect of cooperative hunting for multi-robotic fishes, escape strategy can be used move along a direction simply, random movement or with a complex of intelligent strategy. In order to reflect the agonistic behavior between hunt-robotic fish and the intruder, this paper will consider two cases to design intelligent escape algorithm for invasion-robotic fish: hunt-robotic fish has formed encirclement to invader and has not yet formed encirclement to invader. The algorithm description as follows:

Step 1 initialization information. Set the center point of target area of intrusion-robotic fish is $G(x_g,z_g)$, the current position is $I(x_I,z_I)$;

Step 2 moving to the target. The invasion-robotic fish move to the point G with velocity V_I and direction $\vec{\theta}_{I1}$ (as in Eq.(4));

$$\begin{cases} \vec{\theta}_{I1} = \dfrac{(x_g - x_I, z_g - z_I)}{\sqrt{(x_g - x_I)^2 + (z_g - z_I)^2}} \\ V_I = V_{\mathrm{h}} - 1 \end{cases} \tag{4}$$

Step 3 judgment of the obstacle. If the distance between invasion-robotic fish and obstacles is less than the safe distance L, the robotic fish will use a mechanism of turning around to avoid collision the obstacle, and the direction of avoidance is that reverse vertical direction of lines from invasion-robotic fish to the center of obstacle.

Step 4 the perceptual judgment. When the hunt-robotic fish get into its detection range, that is, when r≤1500mm and the angle of body direction between hunt-robotic fish and invasion-robotic fish meet the condition of $-360/\mathrm{n}° \le |\theta_H|-|\theta_I| \le 360°/n$, then go to step 6, Otherwise go to step 5;

Step 5 the judgment of target area. If the invasion-robotic fish has reached to the target at this time, indicates that invasion successful, otherwise go to step 2;

Step 6 comparison of D (I, G) and D (I, H_i). If the distance D(I, G) from invasion-robotic fish to the target G less than the distance D(I, H_i) from invasion-robotic fish to each hunt-robotic fish, then go to Step2, otherwise go to step7;

Step 7 judge of encirclement state. If the clockwise maximum angle $\max \theta(H_i, H_j) \ge \pi$ that from invasion-robotic fish to any two hunt-robotic fishes that adjacent, then the hunt-robotic fish has not yet formed encirclement to the invasion-robotic fish, then go to step 8, otherwise go to step 9;

Step 8 escaping to the direction of summations. In the state of has not formed encirclement, invasion-robotic fish regard its current direction of movement and perceived the hunt-robotic fish movement speed vector superposition direction as its escape direction (as shown in Figure 6), the escape speed and direction as the Eq. (5), then go to step 10;

$$\begin{cases} \vec{\theta}_{I2} = \dfrac{\vec{\theta}_{I1}}{\sqrt{(x_I - x_g)^2 + (z_I - z_g)^2}} + \dfrac{\sum_{\mathrm{i}=1}^{n} \vec{\theta}_{hi}}{\sqrt{(x_i - x_I)^2 + (z_i - z_I)^2}} \\ V_I = V_h \end{cases} \tag{5}$$

Step 9 escaping to the direction of middle. In the state of forming encirclement, invasion-robotic fish selects the maximum distance between two adjacent hunt-robotic fish(such as $H_i(x_i,z_i)$, $H_j(x_j,z_j)$), then escapes to the direction of midpoint that their position (as show in Figure 7), the escape velocity and direction as the Eq. (6), then go to step10;

$$\begin{cases} \vec{\theta_{I3}} = \dfrac{(x_m - x_I, z_m - z_I)}{\sqrt{(x_m - x_I)^2 + (z_m - z_I)^2}} \\ V_I = V_h + 1 \end{cases} \tag{6}$$

Step 10 the judgment of safety area. Invasion-robotic fish judges whether or not have entered the safety area in the process of escape, if it has entered the safety area, it indicates escape successfully, otherwise go to step 4.

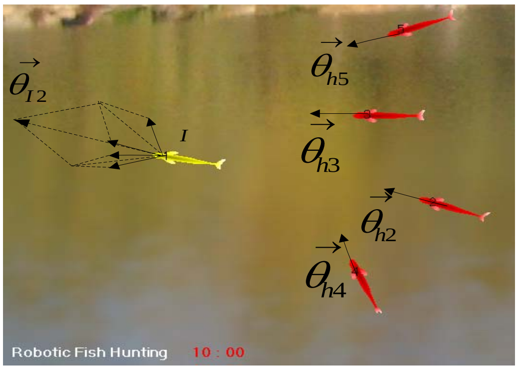

Figure 6. Escape to the direction of summations

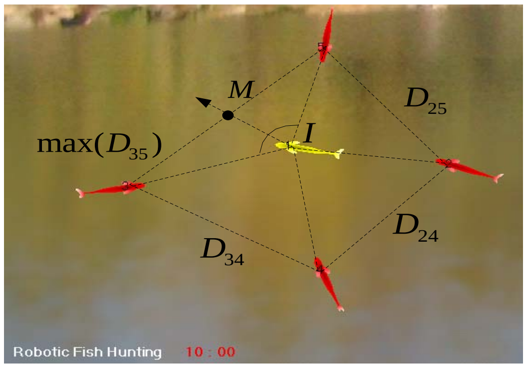

Figure 7. Escape to the direction of middle

6. Simulation Experiments and Results Analysis

Underwater Robot Water Polo Game 2D Simulator platform [9] is an important platform to hold a national underwater robot contest or verifying the theoretical research results, the platform can simulate the change of posture and movement of each joint of underwater bionic robotic fish [10], and meantime, scholars can independent design the simulation environment according to the requirement of the task, and then validate the algorithms and strategies that proposed. On this basis, this paper designed the experimental simulation environment.

6.1. The Design of Simulation

Setting the simulation environment E has one invasion-robotic fish (labeled 1) and four hunt-robotic fishes (labeled 2-5). The state of initial, hunt-robotic fishes randomly distributed in the search area, and invasion-robotic fish randomly distributed in the safety area, in order to ensure that carries on the game behavior of them is invisible in the initial moment; relevant experimental parameters are shown in table 1.

Table 1. The value of the parameter in strategies

Parameters	Values	Instructions
E	(4500,3000)	simulation environment
E_{search}	(3800,3000)	the search target area of hunt-robotic fish
G	(1200,2000)	the center position of target area of invasion-robotic fish
V_h	6	velocity of hunt-robotic fish
V_I	{5,6,7}	velocity of invasion-robotic fish under different conditions
R'/R	1400/500	radius of encirclement; radius of capturing
L	500	The safe distance between robotic fish and obstacles
r	1500	The detection distance of robotic fish
Φ	90°	the level opening angle

6.2. The Experimental Results

The simulation experiment carries on the hunting algorithm simulation in the barrier-free environment and static obstacles environment, such as the table 2, is the average results of carry out 10 times of experiments for each combination of robotic fish with different algorithms under different environments, and compared with the results of the experiment.

Table 2. Comparing the experimental results under different strategies

Environment	Strategy / combination index	Fixed leader		Dynamic adjustment of leader	
		Random escape	Intelligent escape	Random escape	Intelligent escape
Barrier-free environment	Successful rate(%)	73%	70%	94%	91%
	average time (s)	31	36	26	30
Obstacle environment	Successful rate(%)	71%	69%	90%	88%
	average time(s)	40	38	30	36

The process of hunting experiment in barrier-free environment, as shown in Figure 8:

Figure 8a. Hunters choose the area of search

Figure 8b. Hunters have found invader

Figure 8c. Hunters ready to coorperate hunting

Figure 8d. Hunters hunting successful

Figure 8. Robotic fish search target and the process of hunting in barriers-free environment

In Figure 8a, hunters choose the area of responsibility in the state of initial, such as the No. 4 robotic fish chooses area one to search target;

In Figure 8b, hunter5 found invader in the process of searching, it predicted invader's position of next moment and allocated surrounding point for other members, the members move to their point. Invader found oneself has been surrounded at the time, and escape to the direction of velocity vector. In Figure 8c, Hunters have formed the state of encirclement; they will real-time tracking the target with the surrounding point dynamic mobile. In Figure 8d, Shrinking the encirclement and hunters have reached to the catch point, hunting task completion.

The process of hunting experiment that there are three static obstacles in the environment, as shown in Figure 9.

Figure 9a. Robotic fish in the state of the initialize

Figure 9b. hunter2's surrounding point fallen into obstacle area

Figure 9c. Hunter2 moving to the invader

Figure 9d. Hunter2 has released the area of obstacle

Figure 9. Robotic fish the process of hunting under obstacle environment

In Figure 9a, hunters choose the search area of responsibility to search for invader;

In Figure 9b, hunter2 found the invader when it moves to the area of responsibility, predicted invader's position of next moment and allocated surrounding point for other members, and hunter2's surrounding point fallen into the obstacle area;

In Figure 9c, H3H4H5 have reached to the surrounding point, hunter2 given up its expectation surrounding point and moving towards the direction of invader. At the time, invader has been surrounded by hunter3 and hunter5 and escape to the middle direction;

In Figure 9d, Hunter2's surrounding point has released from obstacles area, it will re-participate in the hunting task, by adjusting leader to shrink the encirclement, and hunters have reached the catch point, hunting task completion.

It is visible from the process of the multi-robotic fishes hunting; target search and cooperative hunting strategy that this paper designed can be effectively applied to the hunting task of multi-robotic fishes, and also applies to the obstacle environment, multi-robotic fishes in the basic of quickly complete searching area, can implement the successful hunting to invaders.

6. Conclusion

Based on the problem of multi-robotic fishes target search and cooperative hunting, in this paper separately discussed that the process of searching, hunting and escaping, proposed the partition global search algorithm and based on “dynamic surrounding point” cooperative hunting algorithm. In order to increase the difficulty of hunting task, invasion-robotic fish using an intelligent escape strategy. Through the simulation experiments, it indicates that partition global search algorithm can speed up the search for the intruder and reduce the risk of collision between the robotic fish; “dynamic surrounding point” algorithm that used by hunt-robotic fish can complete hunting task efficiently; and meanwhile, application intelligent escape strategy of invasion-robotic fish could fully reflect the game behavior between the two groups.

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