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NAVIGATION SITUATION ASSESSMENT OF AUTONOMOUS SURFACE VEHICLES IN A COOPERATIVE HUNTING ENVIRONMENT

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ABSTRACT

This paper proposes a navigation situation assessment method for autonomous surface vehicles (ASVs) in a cooperative hunting environment. By virtue of the repulsion function expressed in the artificial potential field, the navigation situation of hunting ASVs and target ASVs is firstly described. And the hunting situation is also constructed to describe the cooperative hunting. Based on the navigation situation and the hunting situation, a navigation situation assessment method for cooperative hunting of multiple ASVs is designed, where the number of hunting vehicles and the hunting radius can be successfully computed. Simulation results show that this proposed situation assessment method can give an optimised formation pattern and provide an effective reference for cooperative hunting of ASVs.

Keywords: autonomous surface vehicles; navigation situation; situation assessment; cooperative hunting

INTRODUCTION

In the past two decades, the cooperative manoeuvring of autonomous marine vehicles, including autonomous surface vehicles (ASVs) and autonomous underwater vehicles (AUVs), has attracted extensive interest [1, 2]. Successful applications can be found in military missions, such as bee-swarm warfare, countermeasure equipment and saturation attacks. Fruitful cooperative manoeuvring methods have been proposed, ranging from cooperative trajectory tracking [3, 4], and cooperative path following [5, 6], to cooperative hunting [7].

The objective of cooperative hunting is to make a fleet of hunting vehicles surround the target vehicle with a circular formation. In this context, the number of hunting vehicles and the hunting radius are topics of concern in academic and engineering circles. These problems are discussed and studied in the research of pursuit-evasion. Utilising the 'differential game', the cooperative hunting problem of two low-speed hunters and one target was investigated by [8]; the boundary gate analysis was completed and the relative positions of the agents were determined. On this basis, amethod of explicit policy was proposed in [9, 10], where the optimal hunting strategies in the minimum time were designed and the trajectories of hunters delineated. In [11], the Apollonius circles formed by the hunters and the target were applied to cooperative hunting, and the hunters cooperatively contained the target by enclosing the target inside a convex polygon. Besides this, in [12], the hunting region and the positions of the hunters were defined using the Apollonius circle mechanism, thus guaranteeing that the hunters were distributed around the target and avoiding collisions between hunters. However, the minimum number of hunters has not been explored for cooperative hunting.

Under a complex and ever-changing marine environment, it is necessary to enable multiple hunting vehicles to sail safely and complete missions successfully, by implementing a situation assessment method. In this context, the artificial potential field (APF) becomes a powerful tool for assessing risk, and various assessment methods have been proposed, based on the APF [13, 14]. It should be noted that the results of situation assessment can provide an effective reference for path planning and collision avoidance [15]. With the aid of the APF, the concept of a driving safety field was first proposed in [16, 17], in order to assess the degree of safety of vehicles. In [18], a driving safety based manoeuvring model was constructed, giving a risk assessment for drivers. In [19], an improved APF was proposed for the safe manoeuvring of ASVs, where appropriate functions and safety requirements are added. In addition to the APF, the supporting vector computer-based assessment method was employed in [20], to obtain the collision risk via vehicle states.

In the literature, situation assessment methods include qualitative assessment and quantitative assessment. Within the qualitative assessment, the changes of situation can be shown and the assessment results for risk and safety cannot be quantified. Within the quantitative assessment, the situation value of each position can be calculated. In [21], a visual analysis-based situation assessment was proposed, using a set of safety indicators which can assess the current states and the efficiency of the current protection mechanism. In [22], the hierarchical Bayesian networks-based adaptive situation assessment method was presented, using information from sensors, thus improving the robustness of the assessment system. Using dynamic Bayesian networks and odourless variance transformation, a situation assessment method is proposed for the tactical behaviour planning of lane changing [23]. By combining the analytic hierarchy process and fuzzy assessment, a fuzzy comprehensive assessment model was constructed for describing the degree of safety and integrating the effective data [24]. In [25], an improved fuzzy neural network-based situation assessment method was proposed for multiple vehicles, improving the intelligence and accuracy of assessments in a complex environment. However, the situation assessment research for cooperative hunting of multiple ASVs is still open for study.

Motivated by these observations, this paper investigates the situation assessment problem of ASVs in a cooperative hunting environment, where one target vehicle is surrounded by multiple hunting vehicles. A novel navigation situation assessment method is proposed for cooperative hunting. Firstly, the navigation situation is constructed based on the potential field, which can describe the degree of difficulty for an object to reach a certain position. Then, by virtue of the circular hunting formation, the interception benchmark angle and the interception positions of hunting vehicles are designed. By iteratively computing the navigation situation and hunting situation, as well as the hunting radius, the navigation situation assessment under different initial conditions is completed, where the number of hunting vehicles and the hunting radius are optimally determined. Finally, simulations are studied by using the proposed situation assessment method and the results show an optimised hunting formation pattern for ASVs in a cooperative hunting environment.

The structure of this paper is as follows. Section II describes the navigation situation. The navigation situation assessment method under cooperative hunting is presented in Section III. Section IV provides simulation results to validate the proposed assessment method. Finally, Section V discusses the conclusions of this research and the direction for further work.

NAVIGATION SITUATION DESCRIPTION

If we consider a network of hunting ASVs, labelled 1 to *n*, and a target vehicle (as shown in Fig. 1), then each vehicle sailing on the ocean produces a single navigation situation that acts in a certain range. The situation values of a hunting vehicle and a target vehicle are usually different. By combining the single navigation situations, the whole navigation situation generated by all ASVs can be generated.

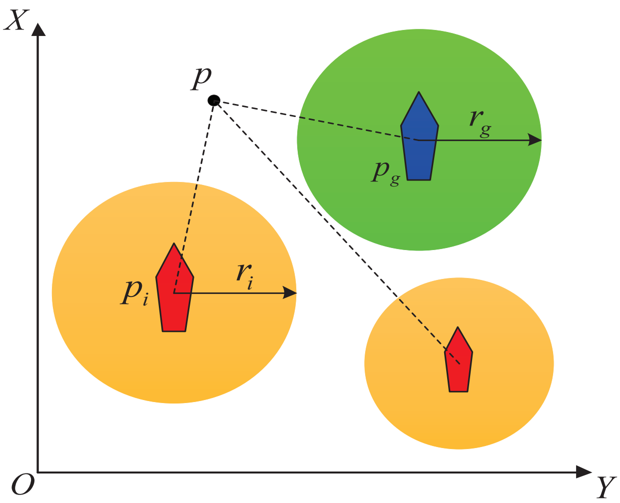


Fig. 1. Navigation situation of two hunting vehicles and one target

With the aid of APF [26], the navigation situation for any point in the earth-fixed inertial frame can be described as

$$T_n(p) = \sum_{i=1}^{n} T_{ci}(p) + T_g(p) \quad (1)$$

where $i = 1, \ldots, n$; $p = [x, y]^T$ is the position of any point in the earth-fixed inertial frame; $T_{ci}(p)$ and $T_g(p)$ denote the single navigation situation generated by the *i*th hunting ASV and the target ASV, respectively. To be specific:

$$T_{ci}(p)=\begin{cases}\frac{1}{2}k_{ci}\left(1+v_{ci}\right)\left(\frac{1}{r(p,p_i)}-\frac{1}{r_i}\right)^2, & 0\le r(p,p_i)\le r_i\\ 0, & r(p,p_i)>r_i\end{cases} \tag{2}$$

and

$$T_g(p)=\begin{cases}-\frac{1}{2}k_g\left(1+v_g\right)\left(\frac{1}{r(p,p_g)}-\frac{1}{r_g}\right)^2, & 0\le r(p,p_g)\le r_g\\ 0, & r(p,p_g)>r_g\end{cases} \tag{3}$$

where k_{ci} and k_g are positive constants; p_i and p_g are the positions of the hunting vehicles and the target vehicle, respectively; v_{ci} and v_g are vehicle velocities; r_i and are the situation detection ranges of ASVs; $r(p,p_i)=\|p-p_i\|$ denotes the distance between the *i*th hunting ASV and the point p; and $r(p,p_g)=\|p-p_g\|$ denotes the distance between the target ASV and the point p.

It should be noted that the relationship of hunting ASVs and the target ASV is confrontational and, because of this, the situation value in (2), generated by the hunting vehicles, is positive and the value in (3), generated by the target vehicle, is negative.

It can be seen that the navigation situation has similar properties with the APF [27]. When the situation value of the point p is positive, it indicates that the target vehicle is subject to resistance and the effects become stronger if the situation value becomes larger. When the situation value of the point p is negative, it means that the hunting vehicles are subject to resistance and the effects will become stronger if the situation value becomes smaller.

Moreover, the navigation situation also describes the sailing safety range and the safety degree of hunting and/or target ASVs. Using Eq. (1), the sailing safety degree can be expressed from a global perspective. The position where the situation value is positive indicates that the target ASV is in danger and the higher the situation value is, the higher the degree of threat. The position where the situation value is negative indicates that the hunting ASVs are in danger; the smaller the situation value, the higher the degree of threat.

In order to describe the cooperative hunting, the hunting situation T_h is defined as

$$\begin{cases}\sum_{i=1}^{n}\frac{1}{2}k_{ci}\left(1+v\right)\left(\frac{1}{r(p,p_i)}-\frac{1}{r_0}\right)^2-\frac{1}{2}k_g\left(1+v\right)\left(\frac{1}{r(p,p_g)}-\frac{1}{r_g}\right)^2>T_h\\ \min\left\{\frac{r(p,p_1)}{v_{1\max}},\frac{r(p,p_2)}{v_{2\max}},\ldots,\frac{r(p,p_n)}{v_{n\max}}\right\}<\frac{r(p,p_g)}{v_{g\max}}\\ r(p,p_g)\le R\end{cases} \tag{4}$$

where v is the vehicle's velocity after cooperative hunting; $v_{1\max},v_{2\max},\ldots,v_{n\max}$ are the maximum velocities of hunting ASVs; $v_{g\max}$ denotes the maximum velocity of target ASV; and R denotes the hunting radius.

It should be noted that, for the point p satisfying $T_n(p)>T_h$ the hunting vehicles can arrive in advance and generate positive situation values. Because of this, the target vehicle is forced to stop and the cooperative hunting is achieved. After cooperative hunting, a circular formation pattern will be generated and maintained by the hunting ASVs, and the target ASV will be located at the centre of the circle. All vehicles have the same velocities and maintain a relatively static state.

NAVIGATION SITUATION ASSESSMENT UNDER COOPERATIVE HUNTING

In this section, a navigation situation assessment method for cooperative hunting of multiple ASVs is proposed, where the number of hunting vehicles and the hunting radius can be efficiently computed. Firstly, cooperative hunting parameters are designed, including the interception benchmark angle and the interception positions. Then, the navigation situation-based assessment method and assessment process are presented, respectively.

COOPERATIVE HUNTING PARAMETER DESIGN

If we consider different types of hunting ASVs and define ASV_j as the *j*th type, where $j=1,\ldots,m$, the interception angle of ASV_1 is θ_1 and the interception angle of ASV_m is θ_m. For the circular hunting formation, the interception positions of ASVs can be solved by the ratio of these interception angles. In this context, we define the proportional coefficients as

$$s_1=\frac{\theta_1}{\theta_m},\quad s_2=\frac{\theta_2}{\theta_m},\ldots,\quad s_{m-1}=\frac{\theta_{m-1}}{\theta_m} \tag{5}$$

and the interception benchmark angle is defined as

$$\theta_r=\frac{2\pi}{s_1a_1^f+s_2a_2^f+\ldots\ldots+s_{m-1}a_{n-1}^f+a_n^f} \tag{6}$$

where a_i^f denotes the numbers of hunting vehicles of different types and $i=1,\ldots,n$.

By virtue of the benchmark angle (Eq. (6)) and the circular hunting formation, vehicles' interception angles can be computed as follows. The interception angle of ASV_1 is expressed by $s_1\theta_r$ and that of ASV_{m-1} is expressed by $s_{m-1}\theta_r$.

Furthermore, interception positions can be employed using the interception angles. The position of ASV_1 is $\left(x_g+R\cos(\alpha),x_g+R\sin(\alpha)\right)$, where α is the initial angle and the neighbouring vehicles' positions can be expressed as follows. Using the ASV_1, the position is $\left(x_g+R\cos\left(\alpha+s_1\theta_r\right),\ x_g+R\sin\left(\alpha+s_1\theta_r\right)\right)$; using the ASV_2, the position is $\left(x_g+R\cos\left(\alpha+0.5\left(s_1\theta_r+s_2\theta_r\right)\right),x_g+R\sin\left(\alpha+0.5\left(s_1\theta_r+s_2\theta_r\right)\right)\right)$; and using the ASV_m, the position is $\left(x_g+R\cos\left(\alpha+0.5\left(s_1\theta_r+\theta_r\right)\right),x_g+R\sin\left(\alpha+0.5\left(s_1\theta_r+\theta_r\right)\right)\right)$.

NAVIGATION SITUATION ASSESSMENT DESIGN

To ensure the safety requirements of hunting ASVs and target ASVs, the safety situation range is defined as R_g. Within this range, the navigation situation value of target ASVs is less than zero. The minimum hunting radius is defined as $R_{\min}$, which satisfies

$$\begin{cases} \sum_{i=1}^{n}\frac{1}{2}k_{ci}(1+v)\left(\frac{1}{R_{\min}-R_g}-\frac{1}{r_i}\right)^2-\frac{1}{2}k_g(1+v)\left(\frac{1}{R_g}-\frac{1}{r_g}\right)^2=0,\ R_{\min}<R_{\max} \\ R_{\min}=R_{\max},\ R_{\min}\geq R_{\max} \end{cases} \tag{7}$$

where $R_{\max}$ denotes the maximum hunting radius.

In this context, the navigation situation assessment conditions are as follows. (a) A circular hunting formation pattern is constructed and the situation value satisfies $T_n(p)>T_h$; (b) the hunting radius satisfies $R\geq R_{\min}$.

It should be noted that, the smaller the number of hunting ASVs, the higher the efficiency of cooperative hunting. In addition to the number of vehicles, the hunting radius is also important. The smaller the hunting radius, the higher the hunting efficiency.

Considering a hunting ASV, with an interception angle of θ_i when intercepting the target ASV alone, if the interception distance is d, then the position of the *i*th hunting vehicle is

$$p_i=\left(x_g+d,y_g\right) \tag{8}$$

and the interception angle θ_i is solved by

$$\begin{cases} y=\tan\left(\frac{\theta_i}{2}\right)x \\ \frac{1}{2}k_{ci}(1+v)\left(\frac{1}{r(p,p_i)}-\frac{1}{r_i}\right)^2-\frac{1}{2}k_g(1+v)\left(\frac{1}{r(p,p_g)}-\frac{1}{r_g}\right)^2=T_h \end{cases} \tag{9}$$

After completing the cooperative hunting, the number of hunting ASV_j is A_j, which satisfies

$$\begin{cases} A_1\theta_1+A_2\theta_2+\ldots+A_m\theta_m\leq 2\pi+\theta_{\min} \\ A_1\theta_1+A_2\theta_2+\ldots+A_m\theta_m\geq 2\pi \end{cases} \tag{10}$$

where $A_j\in N$ and $\theta_{\min}=\min\{\theta_1,\theta_2,\ldots,\theta_m\}$.

Then, we define a set $D=\{d_1,d_2,\ldots,d_m\}$ as the solution to Eq. (10), and it can be concluded that

$$d_f=\left\{a_1^f,a_2^f,\ldots,a_m^f\right\} \tag{11}$$

where $d_f\in D$.

The proposed navigation situation assessment method is employed to solve the optimal cooperative hunting formation. By iteratively computing the navigation situation and hunting situation, the hunting radius and the number of hunting ASVs can be obtained by using the available information regarding hunting vehicles and target vehicles. Fig. 2 shows the assessment process, thus:

Step 1: Using Eq. (9) and Eq. (10), the set $D=\{d_1,d_2,\ldots,d_m\}$ and the number of ASVs can be determined. Let $f=1$ and $a^f=a_1^f+a_2^f+\ldots+a_m^f$. The initial conditions of ASVs can be determined by $H=\{h_1,h_2,\ldots,h_s\}$.

Step 2: Under h_z with $z=1$, the positions of vehicles are initialised using Eq. (5) and (6). Number the vehicles ranging from 1 to a^f and save the current information into the set $\{A\}$.

Step 3: Remove the vehicle labelled j and compute $R_{\min}$ using Eq. (7). Renumber the vehicles and save the current information into the set $\{B\}$. If $j=a^f$, then let $a^f=a^f-1$; otherwise, let $j=j+1$.

Step 4: If assessment conditions are satisfied, save the set $\{A\}$ into the set $\{C\}$ and reset set $\{A\}$ and set $\{B\}$.

Step 5: if $z=s$ and $f=m$, then the cooperative hunting formation is available; otherwise, Step 1 is re-executed.

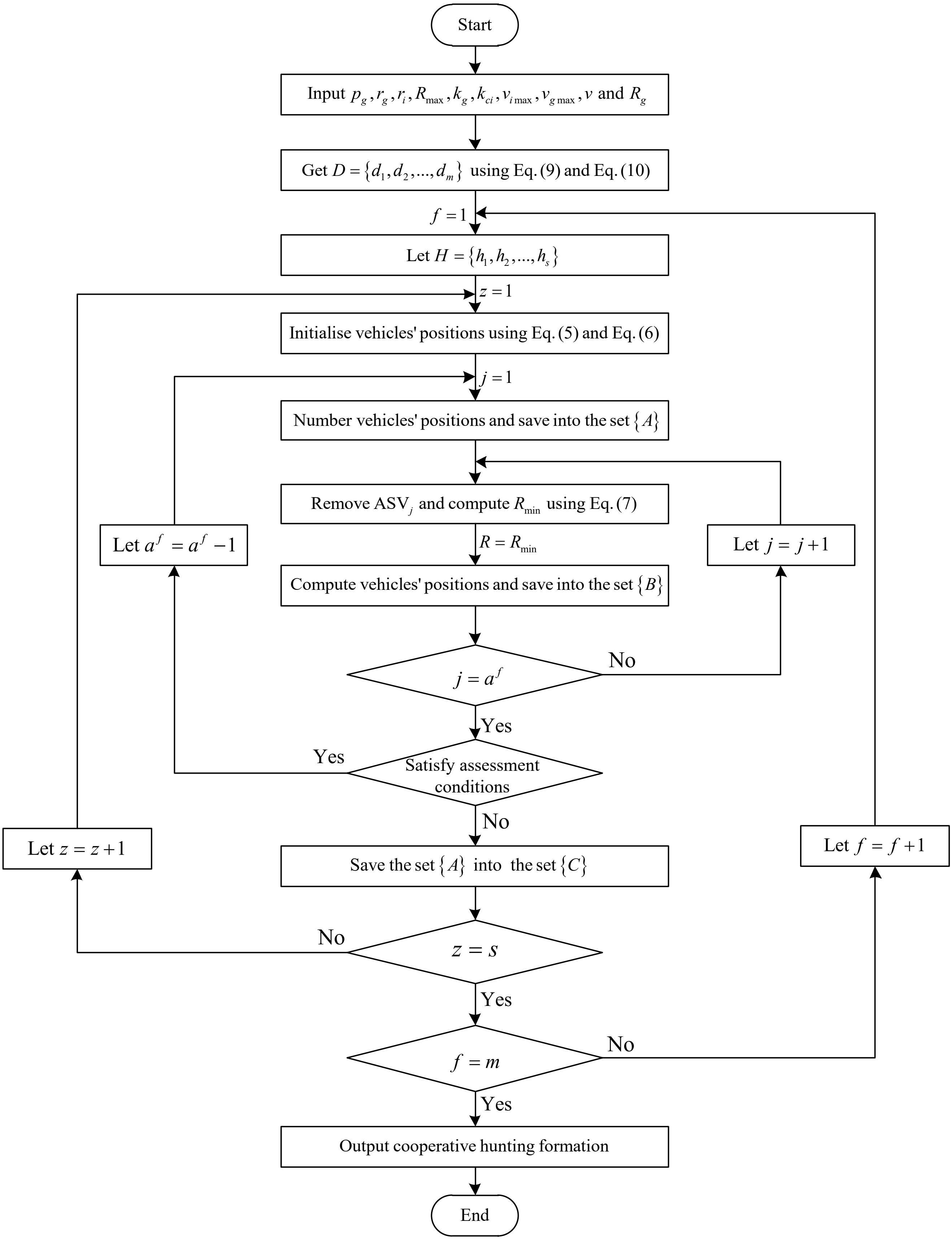
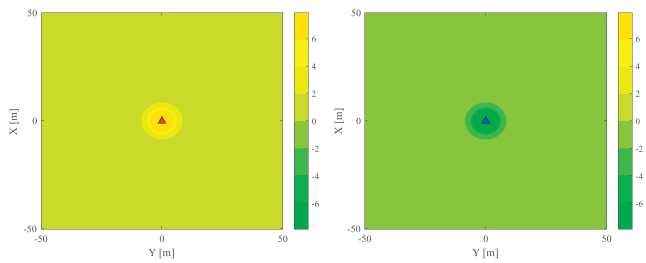


Fig. 2. Assessment process

SIMULATION RESULTS

In this section, simulation studies are conducted to verify the proposed navigation situation assessment method. Two types of hunting ASVs and one target ASV are considered in a cooperative hunting environment. The parameters of the hunting vehicles are as follows: $k_1 = 60$, $v_{1\max} = 8$, $k_2 = 80$, $v_{2\max} = 10$. The parameters of the target vehicle are as follows: $k_g = 60$, $v_{g\max} = 8$, where standard SI units are denoted. The parameters of cooperative hunting are as follows: $R_{\max} = 15$, $R_g = 3.5$, $r_i = 80$, $r_g = 80$, $v = 5$ and the position of the target ASV is $p_g = (0,0)$. Using Eq. (5) and (6), one can conclude that $\theta_1 = 72.2$ and $\theta_2 = 81.6$. Moreover, the set $D = \{d_1 = \{0,5\},\ d_2 = \{1,4\},\ d_3 = \{2,3\},\ d_4 = \{3,2\},\ d_5 = \{4,1\},\ d_6 = \{5,0\}\}$ is also computed. The navigation situation generated by the hunting ASV and the target ASV is shown in Fig. 3. The target vehicle is located at the origin of the earth-fixed inertial frame. The colour presents the strength of navigation situation. Fig. 3 (a) shows that the nearer to the hunting vehicle, the larger the situation value becomes. Fig. 3 (b) shows that the nearer to the target vehicle, the smaller the situation value becomes. The navigation situation value of the target ASV is less than zero.



(a) The hunting ASV *(b) The target ASV*

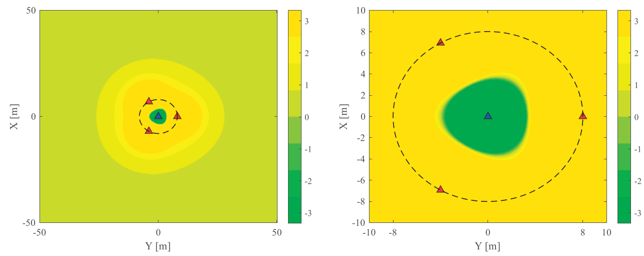
Fig. 3. Navigation situation of ASVs

With the aid of the proposed assessment process, the hunting radius and the number of hunting ASVs are successfully computed for different initial conditions. The assessment results are shown in Table 1.

Tab. 1. Assessment results

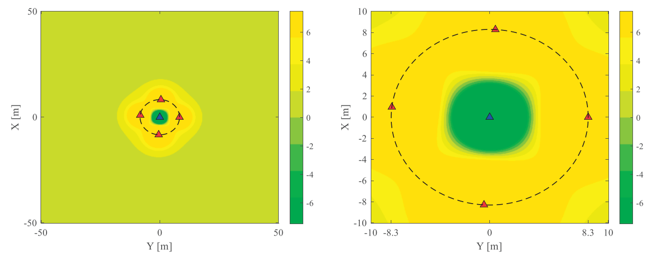
Initial conditions	The number of ASV1	The number of ASV2	The hunting radius (m)
$d_1 = \{0,5\}$	0	3	8.00
$d_2 = \{1,4\}$	0	3	8.00
$d_3 = \{2,3\}$	0	3	8.00
$d_4 = \{3,2\}$	3	1	8.30
$d_5 = \{4,1\}$	4	0	7.84
$d_6 = \{5,0\}$	4	0	7.84

Under the initial conditions of D1, D2 and D3, the optimal hunting formation pattern is constructed by three ASV2s, where the hunting radius is 8.00 m. The cooperative hunting results are shown in Fig. 4, including the global situation and the local situation. Under the initial condition D4, the optimal hunting formation pattern is constructed by three ASV1s and one ASV2 and the hunting radius of the circular formation is 8.30 m. The cooperative hunting results are shown in Fig. 5, including the global situation and the local situation. Under the initial conditions D5 and D6, the optimal hunting formation pattern is constructed by four ASV1s, where the hunting radius is 7.84 m. The cooperative hunting results are shown in Fig. 6. Within the region near to the target vehicle, the situation value is negative and is described by the green area. The region in deep yellow denotes where the navigation situation value is greater than or equal to the hunting situation value, indicating that the cooperative hunting is successful.



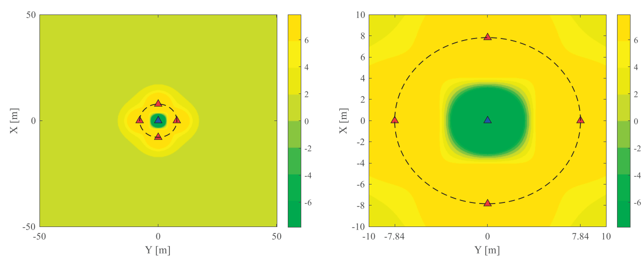
(a) The global situation *(b) The local situation*

Fig. 4. Cooperative hunting results under D1, D2 and D3



(a) The global situation *(b) The local situation*

Fig. 5. Cooperative hunting results under D4



(a) The global situation *(b) The local situation*

Fig. 6. Cooperative hunting results under D5 and D6

When the number of hunting ASVs and the hunting radius are considered simultaneously, the cooperative hunting results shown in Fig. 4 are optimal, where three ASVs are used and the hunting radius is 8.00 m. Three vehicles achieve the even distribution on the circle.

CONCLUSIONS

This paper investigates the navigation situation problem of ASVs in a cooperative hunting environment, where multiple hunting ASVs and one target ASV are considered. The concept of navigation situation is proposed, which can describe the degree of difficulty for an object to reach a certain position; the navigation situation of hunting ASVs and target ASVs is also proposed. Then, a navigation situation assessment method for cooperative hunting of ASVs is proposed and the cooperative hunting parameters are designed, including the interception benchmark angle and the interception positions. Besides this, the number of hunting vehicles and the hunting radius are successfully computed under six initial conditions. Simulation results show that under the given hunting environment parameters, three ASVs are used and the hunting radius is 8.00 m.

In our future work, multiple targets with different hunting situations will be accommodated within the proposed navigation situation assessment method. With the aid of task allocation and navigation situations, multiple hunting ASVs and multiple target ASVs will be researched.

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