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# A real-time obstacle avoidance method for multi-AUV cluster based on artificial potential field

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**Abstract:** [**Objectives**] This paper proposes a real-time obstacle avoidance method based on artificial potential field, in order to cope with the many potential obstacles in complex underwater environment which affects the movement plan for multi-autonomous underwater vehicle (AUV) cluster. [**Methods**] Firstly, a formation method based on dynamic network topology is adopted, and the AUV is regarded as a node in the network. The potential field function is set to meet the formation requirements. Then, based on the artificial potential field method, the potential field function is established for the region where both targets and obstacles exist simultaneously. Afterwards, the potential field function is upgraded to an exponential function, such that the AUVs can be planned online for real-time accomplishment of the mission of obstacle avoidance for multi-AUV cluster. Finally, 10 AUVs and 6 obstacles are simulated with Matlab software. [**Results**] The simulation results show that with this method, each AUV can successfully avoid obstacles and reach the safe area at the target point. [**Conclusions**] The artificial potential field function method may enable the multi-AUV to accurately avoid obstacle in real time. The advancement of this technology has important and positive significance for improving military operational capability.

**Key words:** Autonomous Underwater Vehicle (AUV); artificial potential field; movement in a cluster; formation control; obstacle avoidance

**CLC number:** U664.82

## 0 Introduction

As Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UAVs) and robot soldiers gradually show more and more power on the battlefield, the development of unmanned battle has shown a relatively clear blueprint. Intelligent unmanned vehicles in ocean space such as Unmanned Surface Vehicle (USV), Autonomous Underwater Vehicle (AUV) and Unmanned Underwater Vehicle (UUV), have also developed rapidly, which have begun to play an increasingly important role in the future marine territorial security and marine development. Great importance has been paid to the research in this field in China and abroad, and many encouraging results have been achieved, which has been gradually applied in military and other fields [1].

Movement in a cluster is a very common phenomenon in nature, which is typically represented by the collective flight of birds, the collective migration of insects, and even the collective movement of proteins and other substances in life bodies [2-5]. In the similar movements of these groups, how to form a coordinated and orderly collective movement mode and how to quickly change the current movement state has been a hot issue in the research of cluster move-

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ment control. In the movement formation method of multi-AUV cluster, there are many problems to be considered, such as stability and controllability. To solve these problems, many scholars have proposed their own ideas, such as Leader-follower method, behavior-based method, graph theory method and artificial potential field method [6].

Balch et al. [7] proposed a behavior-based formation method, which decomposes formation control into a series of basic behaviors and realizes motion control through the integration of behaviors. This method has explicit formation feedback and achieves distributed control, but it has no clear definition of group behavior, which is difficult to carry out mathematical analysis, and cannot guarantee the stability of formation.

Pan et al. [8] proposed a virtual structure method, namely that the AUV formation as a whole is regarded as a virtual structure of a rigid body, and each AUV is a fixed point on the rigid body with fixed relative position. This method can control the motion of AUV by defining the behavior of rigid body, but it cannot change the formation according to the change of environment, so its application scope is limited.

Yu et al. [9] studied a Leader-follower method, which divides AUVs into groups of two, namely, one leader AUV with one follower AUV. The formation control can be achieved by keeping certain angle and distance between followers and leaders. According to the relative position relationship between leaders and followers, different network topologies can be formed. When they encounter obstacles in the environment, the obstacles can be avoided by changing the formation. However, the self-adaptability and robustness of this master-slave strategy are not strong enough to fully reflect the ability of individuals in nature to select or track their own targets.

Khatib[10] first proposed the concept of artificial potential field, which assumes that the individual in the field moves in the direction of the minimum potential energy function when subjected to the force of the target and obstacle. In the early stage, this method was only used in static environment, but in dynamic environment, because many dynamic factors were neglected, only relative position was chosen as input. To solve these problems, Khatib improved the method to combine it with other methods, which is more suitable for multi-AUV formation control.

Liu et al.[11] proposed that clustering of cluster movement should be studied in the field of formation control, because clustering emphasizes the movement differentiation in the cluster, and different target tasks can be achieved through different groups, such as obstacle avoidance and tracking. However, they only built theoretical models for this problem and experimental verification lacked. The number of AUVs has an important influence on the navigation and control algorithm of multi-AUV cluster motion. The larger number of AUVs leads to more difficult control.

Combining the above problems, a cluster motion control method based on dynamic network topology and an obstacle avoidance method based on artificial potential field method were proposed in this paper, which improves the artificial potential field function, and verifies the feasibility of the algorithm through simulation experiments with Matlab software.

## 1 Basic model of cluster motion

It is assumed that the control law of the $i^{\text{th}}$ AUV is $\boldsymbol{u}_i$, and

$$\boldsymbol{u}_i = u_i^{\alpha} + u_i^{\text{o}} + u_i^{\gamma} \tag{1}$$

where $u_i^{\alpha}$ is the formation control law, $u_i^{\text{o}}$ is the obstacle avoidance control law, and $u_i^{\gamma}$ is the control law of moving toward the target point. According to these three sub-control laws, AUV is controlled [12].

Considering the cluster consisting of $N$ AUVs, the dynamic equation is

$$\begin{cases}\dot{\boldsymbol{q}}_i = \boldsymbol{p}_i \\ \dot{\boldsymbol{p}}_i = \boldsymbol{u}_i\end{cases}$$

$$i \in \mathbf{Z};\ \boldsymbol{q}_i, \boldsymbol{p}_i, \boldsymbol{u}_i \in \mathbf{R}^2 \tag{2}$$

where $\boldsymbol{q}_i = [x_i, y_i]^{\text{T}}$, which is the individual position; $\boldsymbol{p}_i = [\dot{x}_i, \dot{y}_i]^{\text{T}}$ is the velocity vector; $\boldsymbol{u}_i = [u_{x_i}, u_{y_i}]^{\text{T}}$ is the control input; $\mathbf{Z}$ is the positive integer set; $\mathbf{R}^2$ is the two-dimensional real number set. $\boldsymbol{q}_{ij} = \boldsymbol{q}_i - \boldsymbol{q}_j$, which is the relative distance vector between the $i^{\text{th}}$ and the $j^{\text{th}}$ AUVs.

Each AUV in a cluster is considered as a node in a network oriented digraph. The network topology of AUV will change dynamically in the course of its movement. Using the dynamic network method, the group motion behavior of AUV can be modeled, so that the network node can maintain the balance distance between AUV and its neighbors.

Definition 1 (adjacency graph): Let $G = (v, \varepsilon)$ be a weighted oriented digraph of $n$ nodes, where $v = \{1, 2, \cdots, n\}$ is a set of vertices, and $\varepsilon$ is a set of edges. $\boldsymbol{A} = [a_{ij}]$, which is the weighted adjacency matrix, where for $\forall i, j \in I = \{1, 2, \cdots, n\}, i \neq j, a_{ij} \geqslant 0$; for $\forall i \in I$, $a_{ij} = 0$. Let $r$ be the distance between any two AUV nodes, and the adjacent set of node $v_i$ is $N_i$, which is defined as

$$N_i = \left\{ j \in v : \left\| \boldsymbol{q}_i - \boldsymbol{q}_j \right\| < r \right\} \tag{3}$$

where $\|\cdot\|$ is Euclidean norm under $\mathbf{R}^m$ ($\mathbf{R}^m$ is a set of $m$-dimensional real numbers), and for equilibrium distance, $r > 0$. Adjacent network $G(\boldsymbol{q}) = (v, \varepsilon(\boldsymbol{q}))$ can be determined by point set $v$ and edge set $\varepsilon(\boldsymbol{q})$, where the edge set is

$$\varepsilon(\boldsymbol{q}) = \left\{ (i, j) \in v \times v : \left\| \boldsymbol{q}_i - \boldsymbol{q}_j \right\| < r, i \neq j \right\} \tag{4}$$

Obviously, the edge set $\varepsilon(\boldsymbol{q})$ is determined by $\boldsymbol{q}$ ($\boldsymbol{q}$ is the individual position), and $(G(\boldsymbol{q}), \boldsymbol{q})$ is the adjacent structure.

## 2 Research on formation control based on dynamic network topology

Each AUV in the cluster is regarded as a node in the network, and AUV forms a dynamic network in motion. In order to capture obvious spatial order in a real cluster, the geometric structure of AUV cluster nodes is simulated by using grids. We found out a series of $q$ and $n$ nodes, and let these nodes and adjacent nodes maintain the same distance, described by Formula (5) as

$$\left\| \boldsymbol{q}_j - \boldsymbol{q}_i \right\| = d, \quad \forall j \in N_i(\boldsymbol{q}) \tag{5}$$

In the formula, the selection of $\boldsymbol{q}$ affects the expected formation of AUV cluster to a great extent, so it is defined as a lattice object.

Definition 2: The $\boldsymbol{q}$ geometric configuration under the restriction of Formula (5) is regarded as an $\alpha$ lattice with size $d$, and the AUV individual is called an $\alpha$ individual. Several adjacent individuals are connected to form $\alpha$ lattices. The edge lengths of adjacent networks formed by $\alpha$ lattices are equal.

In order to construct a smooth integrated potential field and a corresponding spatial adjacency matrix, a non-negative map of $\sigma$-norm is defined as follows:

$$\|z\|_\sigma = \frac{1}{\varepsilon}[\sqrt{1 + \|z\|^2} - 1] \tag{6}$$

In this paper, the value of $\varepsilon$ remains unchanged. The new norm is established here because $\|z\|_\sigma$ is differentiable at any time and $\|z\|$ is not differentiable at $z = 0$ ($z$ denotes function variable).

Impulse function $\rho_h(z)$ is a scalar function and is smooth between 0 and 1. It is used to construct smooth potential field function and adjacency matrix. The impulse function is selected as follows:

$$\rho_h(z) = \begin{cases} 1, & z \in [0, h) \\ \dfrac{1}{2}[1 + \cos(\pi \dfrac{(z - h)}{(1 - h)})], & z \in [h, 1] \\ 0, & \text{The others} \end{cases} \tag{7}$$

where $h \in (0, 1)$; impulse function $\rho_h(z)$ is in $[1, \infty)$; $\dot{\rho}_h(z) = 0$, $|\rho_h(z)|$ tends to $z$ uniformly. Using this impulse function, the spatial adjacency matrix $\boldsymbol{A}(q)$ can be defined:

$$a_{ij}(\boldsymbol{q}) = \rho_h(\left\| \boldsymbol{q}_j - \boldsymbol{q}_i \right\|_\sigma / r_\alpha) \in [0, 1], \; j \neq i \tag{8}$$

where $r_\alpha = \|r\|_\sigma$, and for any $i$ and $\boldsymbol{q}$, there is $a_{ij}(\boldsymbol{q}) = 0$. When $h = 1$, $\rho_h(z)$ is constant 1 in $[0, 1)$ and 0 in other intervals. Here, the significance of selecting impulse function is to build a matrix depending on the adjacent network with only 0 and 1 matrix elements.

In order to construct a smooth paired potential field, we also introduced the behavioral function $\phi_\alpha(z)$:

$$\phi_\alpha(z) = \rho_h(z / r_\alpha) \phi(z - d_\alpha) \in [0, 1] \tag{9}$$

$$\phi(z) = \frac{1}{2}[(a + b)\sigma_1(z + c) + (a - b)] \tag{10}$$

where $\sigma_1(z) = z / \sqrt{1 + z^2}$; $\phi(z)$ is a non-uniform S-shaped function; $d_\alpha$ is the edge length of the connection network composed of $\alpha$ lattice; $a$, $b$, $c$ are arbitrary real numbers, and $0 < a \leqslant b$, $c = |a - b| / \sqrt{4ab}$ to ensure $\phi(0) = 0$. Paired gravitational or repulsion potential field functions are defined as follows:

$$\psi_\alpha(z) = \int_{d_\alpha}^{z} \phi_\alpha(s) \mathrm{d}s \tag{11}$$

Finally, a distributed control algorithm was proposed to study formation control in multi-AUV cluster motion.

$$u_i^\alpha = c_1^\alpha \sum_{j \in N_i^\alpha} \phi_\alpha(\left\| \boldsymbol{q}_j - \boldsymbol{q}_i \right\|_\sigma) n_{i,j} + c_2^\alpha \sum_{j \in N_i^\alpha} a_{ij}(\boldsymbol{q})(\boldsymbol{p}_j - \boldsymbol{p}_i) \tag{12}$$

The first half of the equation is the distance gradient, and the second half is the velocity uniformity term. $\boldsymbol{n}_{i,j} = \sigma_\varepsilon(\boldsymbol{q}_j - \boldsymbol{q}_i) = \dfrac{\boldsymbol{q}_j - \boldsymbol{q}}{\sqrt{1 + \varepsilon \left\| \boldsymbol{q}_j - \boldsymbol{q}_i \right\|^2}}$ is a vector connecting $\boldsymbol{q}_i$ and $\boldsymbol{q}_j$, where $\varepsilon \in (0, 1)$ is a fixed parameter of the $\sigma$-norm. The algorithm describes the motion rules between any two AUVs, and satisfies three rules proposed by Reynolds about cluster motion.

## 3 Multi-AUV cluster motion planning based on artificial potential field

The basic idea of artificial potential field method is to construct gravitational field $U_{\text{att}}$ and repulsive field $U_{rep}$ at the locations of the target point and obstacle respectively. The corresponding potential field force will attract AUV to move near the target point, and prevent AUV from moving towards the obstacle. Under the ultimate effect of resultant force, AUV will be guided to move towards the target point.

The design of repulsive field function is related to obstacles, and when the function is closer to the obstacles, the repulsion force is larger; the gravitational field function is similar to it. In order to carry out necessary theoretical study on the method, a two-dimensional planar artificial potential field model with static threat was constructed on the basis of simplifying the problem without losing generality[13].

## 3.1 Gravitational field modeling

The function of distance between AUV and target point in two-dimensional plane is defined as

$$\rho(r, g) = \| r(x_1, y_1) - g(x_2, y_2) \| \tag{13}$$

The gravitational field generated is

$$U_{att}(\rho(r, g)) = \xi \| \rho(r, g) \|^m \tag{14}$$

where $r(x_1, y_1)$ refers to the position of AUV; $g(x_2, y_2)$ refers to the position of target point; $m$ is a positive constant, and the value of $m$ is the factor determining the shape of potential field function curve; and $\xi$ is the target potential field coefficient. Here we take $m = 2$, because when $m = 1$, there will be unbounded gravitational field when the gravitational field derivation is conducted, which will cause the AUV to jitter near the target point. Therefore, $m$ takes the minimum value of 2.

The attraction of the target point to AUV is as follows:

$$F_{att} = -\nabla U_{att}(\rho(r, g)) = m\xi \| r(x_1, y_1) - g(x_2, y_2) \|^{m-1} \boldsymbol{n}_{RG} \tag{15}$$

where $\boldsymbol{n}_{RG}$ is the unit vector from AUV to the target point.

In this paper, because the target of AUV is fixed, the relative motion between AUV and target is not considered when designing gravitational potential field (Fig. 1).

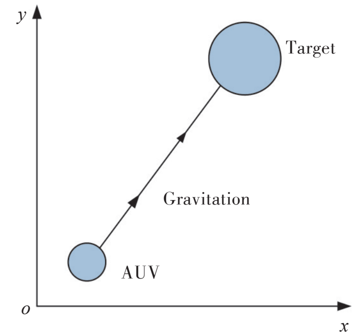


Fig.1 Gravity in two-dimensional space S

## 3.2 Establishment of repulsive field model

The position of obstacle is assumed to be $o(x_3, y_3)$ and $F_{rep1}$ is the repulsion between AUV and the obstacle, which makes AUV move away from the obstacle. Similar to the above analysis, it is assumed that the obstacle is static, regardless of the effect of relative velocity between AUV and the obstacle on the AUV motion. $F_{rep}$ is a repulsion generated by AUV speed, which is proportional to the velocity component on the connection line between AUV and the obstacle, and the direction is along the AUV-obstacle line and away from the obstacle (Fig. 2).

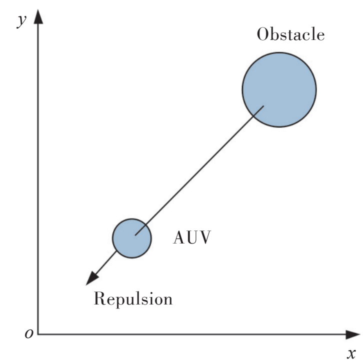


Fig.2 Repulsion in two-dimensional space S

The repulsive potential field is

$$U_{reps} = \sum_{i=1}^{M} U_{reps}(\rho_i(r, o)) \tag{16}$$

where $M$ is the number of obstacles; $\rho_i(r, o) = \| r(x_1, y_1) - o_i(x_3, y_3) \|$ is the distance function between AUV and the $i^{th}$ obstacle. Therefore, Formula (15) can be written as

$$U_{reps}(\rho_i(r, o)) = \begin{cases} \frac{1}{2}\eta\left(\frac{1}{\rho_i(r, o)} - \frac{1}{\rho(r, g)}\right)^2, & \rho_i(r, o) < \rho(r, g) \\ 0, & \rho_i(r, o) > \rho(r, g) \end{cases} \tag{17}$$

where $\eta$ is the coefficient of repulsive potential field.

The repulsion corresponding to the repulsive potential field of the $i^{th}$ obstacle in two-dimensional space S is

$$F_{reps}(\rho_i(r, o)) = -\nabla U_{reps}(\rho_i(r, o)) \tag{18}$$

Therefore, the total repulsion is

$$F_{reps} = \sum_{i=1}^{N} F_{reps}(\rho_i(r, o)) \tag{19}$$

## 3.3 Spatial composite potential field modeling

The gravitational potential field and repulsive potential field in space are synthesized, and the synthesized potential field is obtained as follows:

$$U = U_{att}(r, g) + U_{reps}(\rho(r, o)) \quad (20)$$

The spatial composite potential field force is

$$F = F_{att} + F_{rep} = -\nabla U_{att}(r, g) - \nabla \sum_{i=1}^{N} U_{reps}(\rho_i(r, o)) \quad (21)$$

The independent variable of the conventional artificial potential field function is the square of distance. The curve of this form of function rises and falls too fast, which also makes the gravitation and repulsion change too fast. Therefore, parameter selection is more stringent, and it is likely that the path planning cannot be completed due to the problem of parameter selection. Therefore, the potential field functions adopted here are all improved, and the exponential function is used as the potential field function, whose structure is as follows:

$$U(\rho(r, g)) = \alpha \exp(-X) \quad (22)$$

For gravitational field, the expression of exponential function independent variable $X$ is

$$X = X_{r,g} = \beta \| \rho(r, g) \|^m \quad (23)$$

For the repulsive field, the expression of $X$ is

$$X = X_{r,o} = \gamma \| \rho(\mathrm{r}, o) \|^n \quad (24)$$

When the exponential function is selected, the potential field function is still a function of distance, but the function curve is no longer a quadratic curve, but an exponential curve. According to the characteristics of exponential function, the values of $m$ and $n$ are greater than 1, and the coefficients of gravitational potential field $\beta$ and repulsive potential field $\gamma$ are positive constants, so $X > 0$. And according to the characteristics of exponential function curve, the $U(\rho(r, g))$ image takes the interval part $[0, \infty)$, which changes slowly and is easy to control, thus achieving a relatively stable effect.

## 4 Simulation

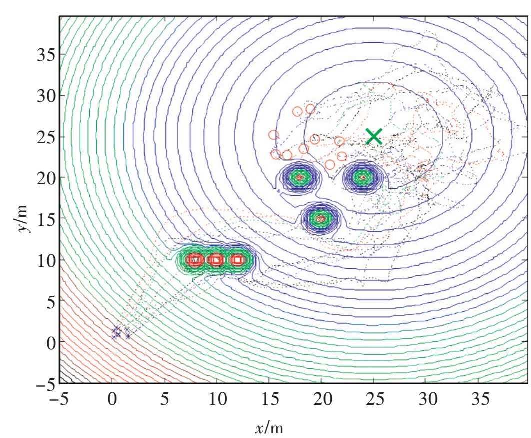
In order to validate the multi-AUV path planning algorithm based on artificial potential field method, the following simulation validation was carried out: Target potential field coefficient $\xi$ was 5; for gravitational field, the number of adjacent individuals $\alpha$ was 5, and the gravitational field coefficient $\beta$ was 0.5; for repulsive field, the number of adjacent individuals $\alpha$ was 1, and the repulsive field coefficient $\gamma$ was 2. Ten AUVs were set up, and the obstacle avoidance motion was completed under the combined action of the gravitation of the target point and the repulsion of the obstacle. The initial velocity of 10 AUVs (unit: m/s) is set to

$$V_{x0} = [16.509, 8.065, 13.032, 3.049, 6.798, 0.386, 15.366, 9.158, 0.871, 1.991]$$

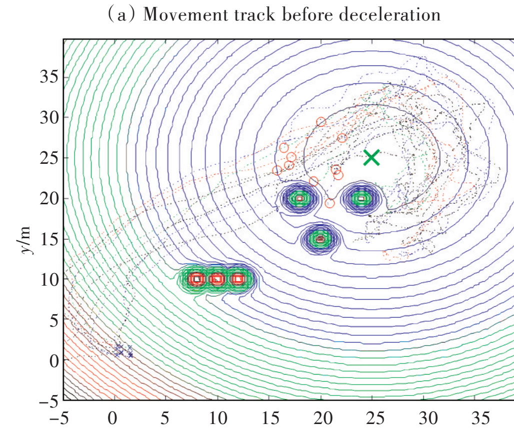
$$V_{y0} = [9.138, 12.176, 4.935, 8.590, 8.599, 0.980, 8.098, 9.565, 13.156, 14.539]$$

In Fig. 3, the "x" sign in the lower left corner represents 10 AUVs, and the "X" sign in the upper right corner represents the position of the target point with the unchanged coordinates; the circles in the plane represent obstacles with coordinates of (80 m, 100 m), (100 m, 100 m), (120 m, 100 m), (180 m, 200 m), (200 m, 150 m) and (240 m, 200 m), respectively; the dashed line is the movement track of 10 AUVs. Fig. 3(b) shows the track of 10 AUVs after a 0.8 m/s deceleration. Fig. 4 shows the movement track of multi-AUV cluster in $x$ and $y$ directions before and after deceleration.

From the simulation results of Figs. 3 and 4, it can be seen that all AUVs can avoid obstacles smoothly and reach the safe area near the target point accurately using the obstacle avoidance method based on the artificial potential field. In the case of slower speed, the AUV is farther from the obstacle, and the collision avoidance effect is better. It can be seen that the artificial potential field method based on exponential function can accurately achieve AUV ob-

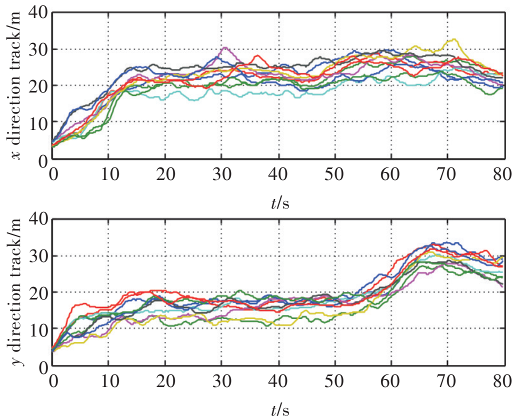



(a) Movement track before deceleration

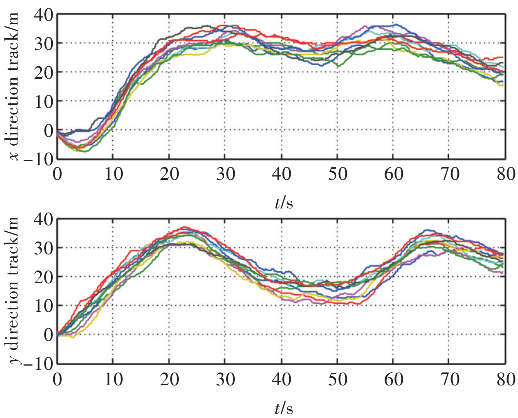



(b) Movement track after deceleration

Fig.3 Multi-AUV cluster obstacle avoidance movement track




(a) AUV movement track in $x$ and $y$ directions before deceleration




(b) AUV movement track in $x$ and $y$ directions after deceleration

Fig.4 Multi-AUV cluster motion trajectories in $x$ and $y$ directions

stacle avoidance.

## 5 Conclusion

Aiming at the problem of keeping clustering and avoiding collision among individuals in multi-AUV cooperative positioning process, in this paper we adopted a formation method based on dynamic network topology, which regards AUV as a node in the network and satisfies the formation requirements by setting potential field function. In addition, aiming at the possible obstacles in navigation, artificial potential field method was used for on-line planning, and the potential field function was simulated as an exponential function. The simulation results show that in the multi-AUV collision avoidance method based on artificial potential field function, the exponential function method can achieve real-time obstacle avoidance for multi-AUV.

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# 一种基于人工势场多AUV集群的实时避障方法

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**摘　要:**[**目的**]针对复杂水下环境中可能存在的多种障碍物,影响多自主式水下机器人(AUV)集群运动规划问题,提出一种基于人工势场的多AUV集群实时避障方法。[**方法**]首先,采用一种基于动态网络拓扑的编队方法,将AUV看作网络中的节点,通过设置势场函数来满足编队要求;然后,基于人工势场法对同时存在目标和障碍的区域建立势场函数,并将势场函数改进为指数函数,对AUV进行在线规划,实时完成多AUV集群避障的任务;最后,在Matlab软件中仿真设置10台AUV和6个障碍物进行仿真验证。[**结果**]仿真结果表明,采用该方法,AUV可以全部顺利地避开障碍物,准确到达目标点的安全区域。[**结论**]人工势场函数法可准确实现多AUV的实时避障,该技术的进步对提高军事作战能力具有重要的意义。

**关键词:** 自主式水下机器人; 人工势场; 集群运动; 编队控制; 避障

[*Continued from page* 37]

# 自主式水下机器人水下对接技术综述

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**摘　要:** 自主式水下机器人(AUV)作为水面支持平台和海底空间站以及深海长期观测系统之间的重要纽带,其水下对接技术一直以来都是国内外的研究热点。在归纳、分析国内外AUV水下对接技术如水下箱(笼)式对接、机械手或载体辅助式对接、杆类引导对接、平台阻拦索式对接和喇叭口式引导对接技术的基础上,介绍各种AUV对接技术的实现方法和结构原理,以及对接技术的发展现状与趋势。并针对目前应用较为广泛的喇叭口式引导对接方式,详细介绍一种针对重型AUV的水下对接系统。经试验验证,该系统模块化强,对横滚姿态要求低,适用于多种尺寸AUV,对接系统的对接成功率高。所做工作可为今后AUV水下对接技术的发展提供参考。

**关键词:** 自主式水下机器人; 水下对接; 结构原理; 喇叭口式引导对接; 综述