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# Tracking and Positioning Technology of Chemical Plumes by Underwater Robots Based on Source Distribution Model

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The hydrothermal vent system will produces a large number of chemical plumes during the eruption process. Relevant characteristics of chemical plumes can be used to navigate underwater robots to achieve the source positioning. This paper establishes the source distribution probability model and obtains the source distribution probability graph by analyzing the motion law of chemical plumes in water. According to the actual water flow environment in the actual searching, the artificial potential field method is improved and the force direction of underwater robots during the motion is obtained through the calculation. Then, the direction of motion of underwater robots is continuously adjusted combined with the source probability distribution graph, finally achieving the tracking and positioning of chemical plumes. At the same time, the overall process of the tracking and positioning of chemical plumes by underwater robots is studied. The main process includes reaching the primary area, starting the first search, discovering chemical plumes, tracing chemical plumes, rediscovery and searching, and source positioning. It provides a reference for the tracking and positioning of chemical plumes by underwater robots.

## 1. Introduction

### 1.1 Literature review

The tracking and positioning of the chemical plumes near the hydrothermal vents are beneficial for the sampling research on the ecosystem of the hydrothermal vent and provide important clues for the study of submarine geology. At this stage, the use of intelligent underwater robots to for the tracking and positioning of chemical plumes has become a research hotspot (Jiu et al., 2015). By studying the olfactory-based bionic detection system, the olfactory-based sensor and identification, searching, tracking and positioning algorithm are constructed on the underwater robot, which can effectively avoid the limitation of vision and auditory in the searching and positioning of chemical plumes. (Deng et al., 2016). Based on the special marine environment, the establishment of the hydrothermal plume model is conducive to the tracking and positioning of underwater robots. At present, in the research on the tracking and positioning of chemical plumes by underwater robots, because of the special underwater environment, chemical plumes are not uniformly distributed and the volume is small. The existing relevant models are relatively single and cannot accurately track and position the target object (Zhang et al., 2012). In order to improve the accuracy of tracking and positioning, scholars propose a discrete hydrothermal plume simulation model to provide technical support for underwater robots. The algorithm for identification, tracking and positioning is written for underwater robots. By establishing the dynamic plume model, the chemical plumes can be accurately tracked and their source can be positioned (Zheng et al., 2016). Internationally, the use of underwater robots for the searching and positioning of chemical plumes has also been a research focus. In the tracking and positioning of chemical plumes in the Pacific and Atlantic Oceans, underwater robots have been applied and outstandingly completed their work (Liu et al., 2012).

### 1.2 Research purposes

With the accelerated development of marine development projects, the research on the use of underwater robots for the tracking and positioning of chemical plumes have received great attention. The traditional positioning method is to lay the chemical plume sensor under water. The data can be collected through the

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sensor and then the collected data is combined with the spatial location of the sensor. Through the analysis of these data, the concentration and the spatial distribution of chemical plumes are obtained. By relevant algorithms, the location of chemical plumes can be roughly estimated (Ji et al., 2012). However, due to the large area of oceans, it is necessary to deploy a number of sensors that are inconvenient to move, which severely limits the working scope and efficiency. Therefore, in order to obtain more accurate information on chemical plumes, it is necessary take the advantages of underwater robots. Robots have high controllability and flexibility and underwater robots can be used for large-scale tracking and positioning. In addition, the usage rate of underwater robots is high and the installation and maintenance are convenient, which effectively solves the problem of traditional inaccurate tracking and positioning, significantly improves the efficiency of the tracking and positioning of underwater chemical plumes and benefits the implementation of marine development projects. At this stage, however, the tracking and positioning of chemical plumes by underwater robots is still in its infancy and the research on its processes and algorithms is still insufficient. Therefore, this paper will study its overall workflow and provide the calculation method needed in the tracking and positioning process, which is of great research significance.

## 2. Outline of relevant theories of tracking and positioning of chemical plumes by underwater robots

Underwater robots integrate artificial intelligence, autonomous detection and identification, information induction and fusion and intelligent control technology on a single carrier to replace the role of human beings in underwater operations (Tian et al., 2012). As the blue state territory, the ocean contains abundant energy and resources. In recent years, due to the increasing scarcity of land resources and the increasing mining difficulty, the development of marine resources has been increasingly valued by various countries. Under this background, the pace of development projects in the marine sector has gradually accelerated. The application prospect of underwater robots in the tracking and positioning of chemical plumes have been increasingly valued and their development direction has become increasingly clear.

Firstly, coordinate the development direction. Multi-robot collaboration is of great use in marine scientific researches and underwater robots play an important role in the investigation of oceanic plumes. With the increase of researches on underwater chemical plumes, the workload of underwater robots has gradually increased and the work content has become more complex (Wang et al., 2014). Compared with a single robot operation, multiple underwater robots can cooperate with each other to complete the collection, induction and integration of through a wide range of monitoring. The multi-robot collaborative decision-making and management give full play to their own characteristics and complete work efficiently. Therefore, the multi-robot collaboration is an important direction for the detection of chemical plumes by underwater robots in the future.

Secondly, the remoting direction. Problems such as large detection area and long detection time can be found in the detection of chemical plumes by underwater robots, which has posed higher requirements for the endurance and working range of underwater robots. It is expected that the detection range of underwater robots will be expanded to 250-5000 km in the future and they are required to work continuously for more than 100 hours underwater. Researches on the power source has also been conducted. At this stage, solar cells supporting its work have been developed. In the working process of underwater robots, if there is a power shortage problem, robots can float to the surface for charging (Fang et al., 2014). It can be seen that remote operations will be an important direction for the future development of underwater robots.

Thirdly, the direction of intelligence. In order to meet the technical requirements of underwater development robots for marine development projects, the underwater robots will be equipped with special equipment to perform certain specific tasks for different sea areas and different seabed environments. Therefore, improving its ability to respond to emergencies is essential. If the robot has this ability, its work will break through the traditional mode of pre-set procedures, accumulate useful information according to the actual situation of the underwater, and continuously improve the accuracy of the collected data. Under normal circumstances, the underwater robot will only transmit the collected data to the staff. The staff will classify and integrate the resource data, making the work inefficient. If the underwater robot can realize the three-dimensional sensing function of the underwater environment from computer software and hardware, the collected information is fed back to the staff, and the staff can make judgments according to the specific environment. However, as artificial intelligence is still in the development stage, the requirements for underwater robots cannot be enhanced in terms of technology. Therefore, applying artificial intelligence technology to the development of underwater robots will be an important direction for future development.

## 3. Research on the tracking and positioning of chemical plumes by underwater robots

### 3.1 Establishing a source probability distribution model

Firstly, the search area is divided into *m* parts in the X direction and *n* parts in the Y direction. $L_x$ and $L_y$ are location in the X and Y direction. The area grid division diagram is shown in the figure below.

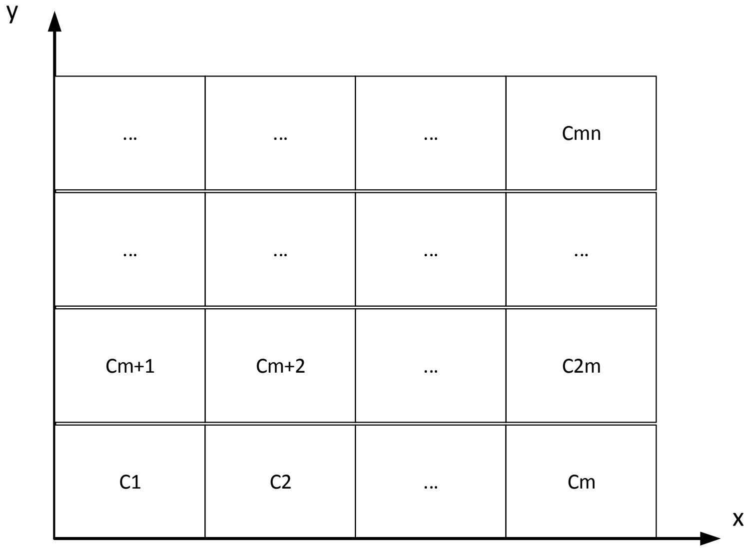


*Figure 1: The search area grid division diagram.*

As chemical plumes move away from the source, the molecular cluster will expand further and the average concentration will decrease. In this process, the intermolecular interaction force leads to random motion and the dispersing force of the flow causes the chemical plumes to move downstream. In the overall motion process of chemical plumes, the intermolecular force makes it produce a small movement range and the motion changes slowly; the dispersing force of the flow makes it produce a large motion range and the motion changes quickly, which is the main factor that determines the underwater motion of chemical plumes. According to the theory of the Gaussian plume physical model, a single plume molecule moves downstream under the effect of flow, forming a diffusion centerline. At the same time, due to the molecular Brownian motion, the chemical plume molecule will deviate from the centerline and do random motion. The chemical plume diffusion model is established under this idea and the position of a single plume chemical filament is $\dot{X}(t) = U(X,t) + N(t)$. In this formula, $X$=($x$, $y$) is the position of chemical plumes; $U$=($u_x$, $u_y$) is the mean velocity of the flow; $N$=($n_x$, $n_y$) is the random function whose variance is $(\sigma_x^2, \sigma_y^2)$ and mean value is 0. When the source releases chemical plumes at $t_l$ and develops to $t_k (t_k > t_l)$, the position is:

$$X(t_l, t_k) = \int_l^k U(X(t))dt + \int_l^k N(t)dt + X_s \tag{1}$$

In this formula, $X_s$ is the initial position. At $t_k$ moment, the mean value of the position of chemical plumes is:

$$\overline{X}(t_l, t_k) = \int_l^k U(X(t))dt + X_s \tag{2}$$

When an underwater robot detects a chemical plume at $t_k$, the possible position of the heat is:

$$X_s(t_l, t_k) = X(t_k) - \int_l^k U(X(t))dt - \int_l^k N(t)dt \tag{3}$$

Set W($t_l, t_k$)=$\int_l^k N(t)dt$, its probability density function is:

$$f(w_x(t_l,t_k)) = \frac{e^{\frac{w_x^2}{2(t_k-t_l)\sigma_x^2}}}{\sqrt{2\pi(t_k-t_l)\sigma_x^2}}, \quad f(w_y(t_l,t_k)) = \frac{e^{\frac{w_y^2}{2(t_k-t_l)\sigma_y^2}}}{\sqrt{2\pi(t_k-t_l)\sigma_y^2}} \tag{4}$$

$$S_{ij}(t_l,t_k) = \frac{1}{\sqrt{2\pi(t_k-t_l)\sigma_x\sigma_y}} \int_{-\frac{L_x}{2}}^{\frac{L_x}{2}} e^{\frac{(x_j-x_i-v_x(t_l,t_k)-x)^2}{2(t_k-t_l)\sigma_x^2}} dx \times \int_{-\frac{L_Y}{2}}^{\frac{L_Y}{2}} e^{\frac{(y_j-y_i-v_y(t_l,t_k)-y)^2}{2(t_k-t_l)\sigma_y^2}} dy \tag{5}$$

In this formula, $S_{ij}$ represents the probability of a filament generated by the source in $X_l$ at $t_l$ moment moving to $X_k$ at $t_k$ moment. By traversing all positions in the searching area, the probability of the source at any position can be obtained, obtaining the source distribution probability graph.

### 3.2 Analysis of the tracking process

According to the actual situation, the tracking and positioning of chemical plumes by underwater robots is mainly divided into five processes. The specific process is shown in the figure below.

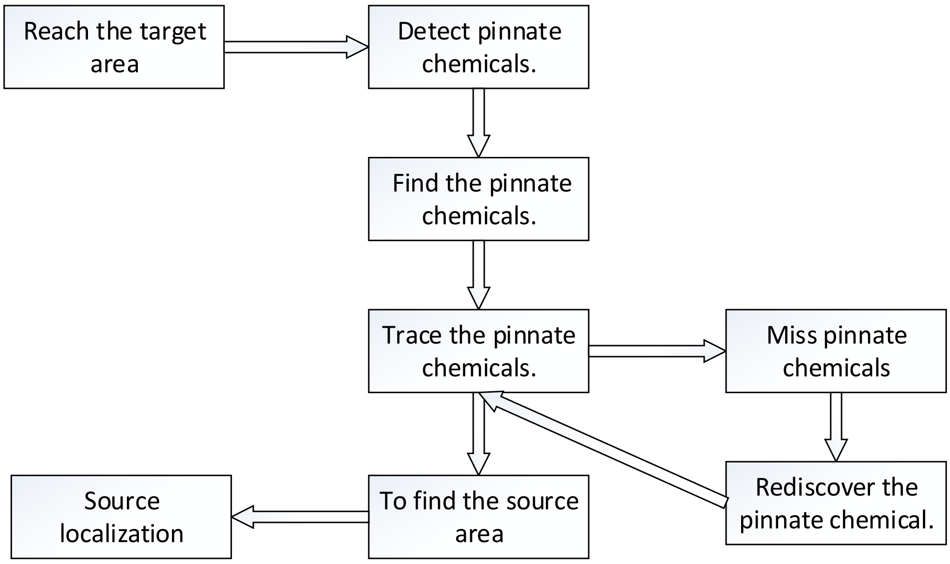


*Figure 2: Flowchart of the tracking and positioning of chemical plumes by underwater robots*

In the first step, an instruction is given and the underwater robot reaches the designated position in the target area at full speed.

The second step is to search for chemical plumes. At this stage, the underwater robot will search the target area. Since the chemical plume will travel downstream with the flow, the underwater robot will start the searching from the downstream of the target area and the initial motion direction will be set vertical to the flow direction. If the chemical plume is detected, it will switch to the tracking mode. If no chemical plume is detected at the boundary, the heading of the robot will be adjusted. Specifically, $\Psi_f \pm 90 \pm 20$ can be selected, where the $\Psi_f$ is the flow direction.

The third step is to track the chemical plume. Based on the detection of chemical plumes, the underwater robot will track the chemical plume by adjusting its motion direction. The angle between the motion direction and the counter flow direction is $\beta \in [20,70]$. In order to obtain the corresponding operating angle of underwater robots at different times and realize the effective tracking of chemical plumes, this paper studies the entire tracking process by introducing the method of artificial potential field planning and combining the source probability distribution. The so-called artificial potential field is to define the environment of the target area as a virtual space. In this space, there exists a virtual potential field, which exerts a force on the robot. The virtual potential field specifically includes a gravitational field and a repulsive field. In the artificial potential field, the potential function is $U = U_o + U_g$ and the force that the robot receives under the water is $F = F_o + F_g$, where $F_o$ is the repulsive force that the underwater robot receives and $F_g$ is the gravity that it receives. The specific calculation method is:

$$F_o = -grad(U_o) = -\{\frac{\partial U_o}{\partial x} i + \frac{\partial U_o}{\partial y} j + \frac{\partial U_o}{\partial z} k\} \tag{6}$$

$$F_g = -grad(U_g) = -\{\frac{\partial U_g}{\partial x} i + \frac{\partial U_g}{\partial y} j + \frac{\partial U_g}{\partial z} k\} \tag{7}$$

Since there are few obstacles in the actual tracking environment and the repulsion does not exist in general situation, so this paper only considers the impact of the gravitational field on the underwater robot. Due to the uncertainty of the source of chemical plumes, in order to realize the tracking and positioning, it is necessary to calculate the probability distribution graph of the source and generate a gravitational field based on this. Then, the instruction can issued to guide the motion of robots. In the source probability distribution graph, there is a source probability value for each coordinate. The greater the value, the more likely that there is a source. During the detection process of underwater robots, a series of probe feedback will be obtained. Using the probability estimation method, the source probability distribution graph will be updated in according to the real-time feedback. When detecting the robot is detecting in the flow field, a $w \times w$ grid is generated centering on it and the motion direction of robots is calculated by the artificial potential field method. Figure 3 is a schematic diagram of an improved artificial potential field method.

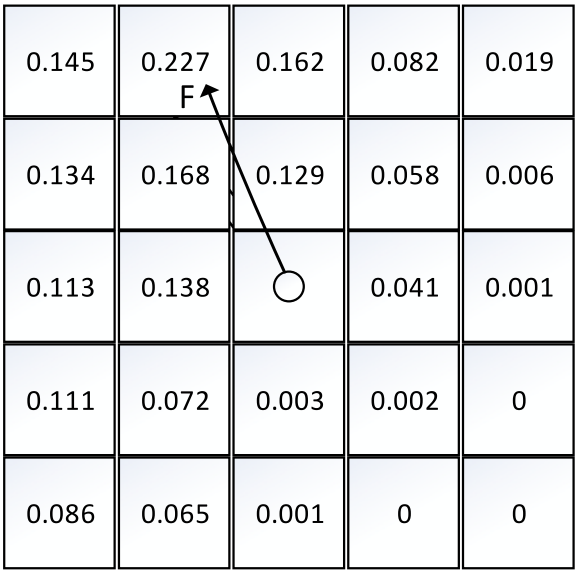


*Figure 3: Schematic diagram of the improved artificial potential field method*

In Figure 3, the robot in the center and the direction of the arrow is the direction of the potential field force received by the robot. The data in the grid represents the source probability value, which will generate a virtual gravity for underwater robots. The probability value and the distance from the robot determine the virtual gravity. The gravity generated by each cell for the robot is $F = \frac{PV_i}{ds}(\frac{L_v - L_i}{ds})$, $F = \frac{PV_i}{ds}(\frac{L_v - L_i}{ds})$. In the formula, *PV* is the source probability and *ds* is the distance between the grid position and the robot. The join force of the virtual gravity generated by all grids on the robot is calculated, $F = \sum_{i \in w} F_i$. The direction of the joint force is the direction in which the underwater robot will move. After the motion in the given direction for a certain period of movement, if a new chemical plume is detected, the source probability graph is updated and the motion direction is recalculated. If not, it will switch to the rediscovery stage of chemical plumes.
In the fourth step, rediscovery of chemical plumes.
When tracking, due to the randomness of the distribution of chemical plumes, the underwater robot might lose its information. At this time, it will enter the rediscovery stage. In this stage, the searching is conducted using the clover searching path and the searching is conducted from the final detection point.

The fifth step, source positioning. Set the threshold value as $\tau$. When there is a grid in the probability distribution graph and the probability value is greater than the threshold value $\tau$, it will switch to the source confirmation link. Since the detection position will be returned at each time when the chemical plume is detected, a rectangular searching is performed near the maximum probability grid. According to the detection result, the range is continuously narrowed and the source positioning is finally achieved.

## 4. Conclusion

In summary, through the establishment of the source distribution model and the application of artificial potential field, this paper studies the specific process of the tracking and positioning of chemical plumes by underwater robots and proposes that the entire tracking and positioning process can be divided into reaching the primary area, starting the first search, discovering chemical plumes, tracing chemical plumes, rediscovery and searching, and source positioning. At the same time, the algorithm for the motion direction of robots in the tracking and positioning process is given, which improves the efficiency and accuracy of the tracking and positioning of underwater robots to a certain extent and provides reference for the application of the tracking and positioning of chemical plumes by underwater robots.

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