Problem Chosen	2024 MCM/ICM Summary Sheet	Team Control Number
B		2429359

Research on Safety Measures and Emergency Response Plans for Deep-Sea Exploration: Dynamics Modeling of Submersibles and Search Strategies

Summary

This paper focuses on safety measures and emergency plans for deep-sea exploration activities, including the motion model of divers, rescue equipment selection strategies, and search strategies. For the six-degree-of-freedom motion of divers, this paper establishes an accurate hydrodynamic model that covers the translational and rotational motion of divers in three-dimensional space. It also specifically considers the impact of environmental factors such as sea water temperature, salinity, and flow rate on the motion of divers and incorporates these factors into the model, thereby improving the accuracy and practicality of the model. In addition, we conducted controlled simulations to determine the impact of uncertain factors on the model and further verify its rationality.

For search tasks, this paper proposes a comprehensive evaluation method based on Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This method first uses AHP to determine the weights of various evaluation indicators and then uses TOPSIS to rank and select different types of rescue equipment. Through this method, this paper successfully provides a rescue equipment purchase selection plan.

In addition, in the search strategy, we innovatively refer to the ant colony and simulated annealing optimization algorithms in optimization algorithms and use computer-aided methods to select search paths. Through this algorithm, we can confirm the optimal search route and improve the efficiency of searching for divers.

In extended applications, this paper simulates and applies the established models and search strategies to deep-sea exploration tasks in the Caribbean Sea. In addition, this paper also uses the depth-first algorithm to optimize the collaborative search strategy in the case of multiple submarines, providing useful references for future collaborative missions of multiple divers.

Overall, the work of this paper mainly focuses on establishing accurate motion models for divers, proposing effective search strategies, and comprehensive evaluation methods. Through these efforts, this paper solves a series of key problems in deep-sea exploration tasks and provides a certain reference for future deep-sea research.

Keywords: Six-degree-of-freedom motion model, Analytic Hierarchy Process, TOPSIS algorithm, Collaborative search strategy.

Contents

1. Introduction

1.1 Background

With the advancement of technology and the increasing desire for human exploration in unknown fields, deep-sea exploration has become a hot topic in recent years. Maritime Cruises Mini-Submarines (MCMS), a company headquartered in Greece, specializes in manufacturing submarines that can carry humans deep into the seabed. These advanced submarines not only provide powerful tools for researchers to study marine biology and seabed terrain, but also bring unprecedented deep-sea experiences to tourists.

In recent years, MCMS plans to use its submarines for commercial tourism, allowing tourists to personally explore the wrecks of the Ionian seabed and feel the weight of history and the mystery of the ocean. However, before officially launching this tourism project, the company must ensure the safety of tourists and formulate a series of safety measures and emergency plans.

Deep-sea exploration is different from land or seaborne search and rescue, with a complex and ever-changing environment full of unknowns. When the submarine loses communication with the mother ship or suffers mechanical failure, it may be in a dangerous situation. Especially in the neutral buoyancy area or seabed, the positioning of the submarine becomes particularly critical. In addition, water flow, changes in sea water density, and seabed terrain may all affect the position of the submarine.

Therefore, to accurately predict the position of the submarine in deep sea, MCMS needs to develop an advanced model. This model not only needs to be able to predict the real-time position of the submarine, but also needs to be able to evaluate the uncertainty of the prediction, and determine which key information the submarine needs to send to the mother ship to reduce these uncertainties. At the same time, in order to ensure timely rescue in emergency situations, MCMS also needs to consider which additional search and rescue equipment to equip on the mother ship, and evaluate the cost-effectiveness of these equipment.

1.2 Restatement of the Problem

Locate - Develop one or more models to predict the submarine's position over time. What are the uncertainties associated with these predictions? What kind of information can the submarine regularly send to the mother ship to reduce these uncertainties before an accident occurs? What equipment does the submarine need to achieve this?

Prepare - What additional search equipment do you recommend the company to carry on the mother ship for contingencies? How should the selection be made, considering the availability, maintenance, and cost of preparation and use of the equipment? If assistance from rescue vessels is needed, what additional equipment might they require?

Search - Develop a model that utilizes your position model information to recommend initial deployment points and search patterns for equipment, in order to minimize the time taken to find a missing submarine. Determine the probability of finding the submarine based on time and accumulated search results.

Extrapolate - How can your model be extended to adapt to other tourist destinations, such as the Caribbean Sea? How will your model adjust when multiple submarines are moving in the same region?

2. Assumptions and Justifications

Assumption 1: Assuming that the physical parameters of the internal environment within a sufficiently small marine space remain the same and unchanged during the search time.

Justification: The ocean is stable within a short period and small range, and is not affected by external factors such as submarines.

Assumption 2: The terrain of the seabed will not cause the submarine to stop moving when it comes into contact, but will change its motion state and make it move in a reasonable direction.

Justification: It is indeed convenient to assume that the submarine gets stuck on the terrain, but in order to simulate more complex situations and respond to emergency rescue situations, we hope to simulate a situation where the submarine does not get stuck on the terrain, thereby increasing the search range.

Assumption 3: The direction and speed of the collected surface ocean current can represent the general trend of the ocean current below the surface, and the ocean current at the seabed is chaotic and unpredictable.

Justification: Our technology cannot fully collect the overall situation of the ocean current below the surface, but we can use a random speed generated by a computer to simulate the undercurrent below the surface.

3. Symbols and Definitions

Symbols	Definitions
m	mass of the submarine
V	speed of the submarine
Ω	angular velocity of the submarine
ρ	density of seawater
T	seawater temperature
S	seawater salinity
C_d	viscosity coefficient

Table 1: General Parameter Description for Papers

4. Task1: Locate

4.1 Six Degrees of Freedom Motion Model

The six degrees of freedom (6DOF) motion model for a submarine is a mathematical representation that describes the submarine's motion, encompassing six degrees of freedom: longitudinal motion, lateral motion, vertical motion, roll motion, pitch motion, and yaw motion.

When establishing the 6DOF motion model for a submarine, the body-fixed coordinate system is typically adopted. This reference coordinate system has its origin at the submarine's center of mass and its axes aligned with the directions of the submarine's motion. Within this coordinate system, the equations of motion for the six degrees of freedom can be defined, describing the submarine's trajectory and attitude.

4.1.1 Body-Fixed Coordinate System

The body-fixed coordinate system (also known as the vehicle coordinate system or moving coordinate system) is attached to the submarine. In this right-handed coordinate system, the origin O is chosen to be at the submarine's center of gravity. The Oy-axis points in the forward direction of the submarine, the Ox-axis is perpendicular to the Oy-axis and points towards the right side, and the Oz-axis is perpendicular to the Oxy-plane, pointing downwards perpendicular to the hull, as shown in **Figure 1**

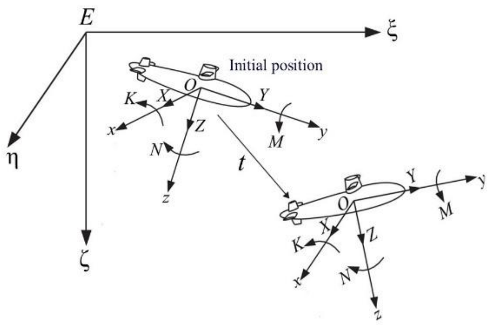

Figure 1: Schematic Diagram of the Body-Fixed Coordinate System for a Submarine

The body-fixed coordinate system is used to describe the submarine's motion relative to itself, such as its attitude angles (roll, pitch, yaw) and angular velocities. By using the body-fixed coordinate system, the submarine's motion state can be more intuitively understood and analyzed.

Under the body-fixed coordinate system, the representations of the submarine's motion and forces in various directions are shown in **Table 2**.

Physical Quantity	X-axis	Y-axis	Z-axis
Velocity V (m/s)	u	v	w
Angular Velocity Ω (°/s)	p	q	r
Force F (N)	X	Y	Z
Moment M (N*m)	K	M	N

Table 2: Representation of Physical Quantities in Different Directions Under the Body-Fixed Coordinate System

4.1.2 Absolute Inertial Reference Frame

The absolute inertial reference frame is an idealized system where Newton's laws of motion take their simplest form, free from any external forces. However, in reality, due to factors such as the Earth's rotation and revolution, a true absolute inertial reference frame does not exist. Therefore, in practical applications, a relatively stable reference frame is chosen to approximate the absolute inertial reference frame.

In this model, the reference frame used to approximate the absolute inertial reference frame is the North East Down (NED) coordinate system, which is a geographic coordinate system. In the NED coordinate system, the N-axis points towards the north of the Earth, the E-axis points towards the east of the Earth, and the D-axis is perpendicular to the Earth's surface and points downwards. The origin of the NED coordinate system is typically located at a specific point on Earth, with the north and east directions representing the x-axis and y-axis of the coordinate system, respectively. In the NED coordinate system, the north direction typically represents the positive x-axis, and the east direction represents the positive y-axis, as shown in **Figure 2**.

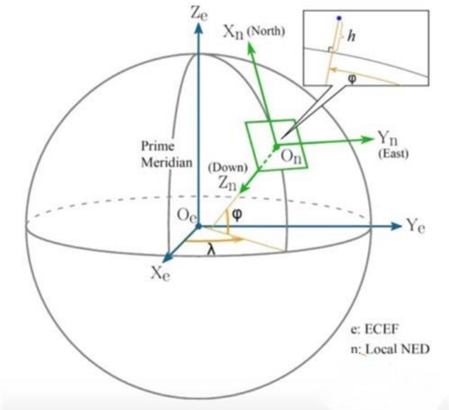

Figure 2 :NED（North East Down）coordinate system

4.1.3 Reference Frame Based on the Moment of the Submersible's Loss of Contact

This reference frame differs from commonly used frames, as it is centered on the moment of the submersible's loss of contact. The origin, O, is located at the submersible's center of gravity at the moment of loss of contact. The Oy-axis is defined as the positive direction pointing towards the bow of the submersible at the moment of loss of contact, while the Ox-axis is perpendicular to the Oy-axis and points in the direction of the starboard side of the submersible at that moment. The Oz-axis is perpendicular to the Oxy plane and points vertically downwards relative to the submersible's hull at the moment of loss of contact, as shown in **Figure 3**.

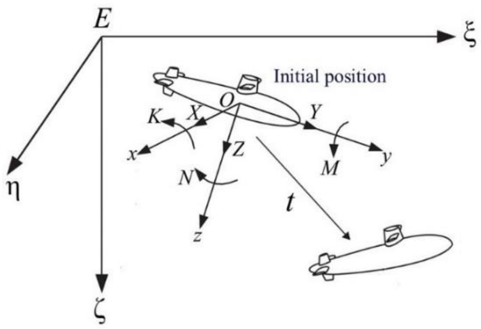

Figure 3: Reference Frame Based on the Moment of the Submersible's Loss of Contact

Unlike a body-fixed coordinate system, the origin and three-dimensional directions of this coordinate system do not change with the movement of the submersible in an absolute inertial reference frame. Its origin position and three-dimensional directions remain constant relative to the ground. This setup is tailored for programming and problem-solving purposes.

Since our objective is to predict the location of the submersible after its loss of contact, starting from the origin of this reference frame, the submersible's initial position coincides with the origin, and its initial attitude directions align with the three-dimensional directions. By applying incremental time steps, the submersible's movement and attitude changes can be simulated. Eventually, by calculating the displacement of the submersible relative to the origin at a given moment, we can directly determine its location. This approach not only simplifies the programming logic but also makes the final result more straightforward.

4.1.4 Influence of External Forces on Motion

Combining the theorem of motion of the center of mass and the theorem of moment of momentum, we can express the physical quantities related to motion and the external forces acting on the object using the following set of equations:

$$\begin{cases} m(\dot{u} + qw - rv) = X \\ m(\dot{v} + ru - pw) = Y \\ m(\dot{w} + pv - qu) = Z \\ I_x\dot{p} + (I_z - I_y)qr = K \\ I_y\dot{q} + (I_x - I_z)rp = M \\ I_z\dot{r} + (I_y - I_z)pq = N \end{cases} \tag{1}$$

Based on equation (1), we can derive the following difference equations:

$$\begin{cases} \Delta u = \left(\frac{X}{m} + rv - qw\right)\Delta t \\ \Delta v = \left(\frac{Y}{m} + pw - ru\right)\Delta t \\ \Delta w = \left(\frac{Z}{m} + qu - pv\right)\Delta t \\ \Delta p = \left(\frac{K}{I_x} + I_y qr - I_z qr\right)\Delta t \\ \Delta q = \left(\frac{M}{I_y} + I_z qr - I_x qr\right)\Delta t \\ \Delta r = \left(\frac{N}{I_z} + I_x qr - I_y qr\right)\Delta t \end{cases} \tag{2}$$

4.1.5 Calculation of External Forces

In the given context, the external forces acting on a submersible are generally divided into two parts: one is the reaction force from the fluid encountered during its movement through the water, which constitutes the hydrodynamic force; the other is the gravity and buoyancy acting on the submersible, which constitute the non-hydrodynamic force.

For the hydrodynamic force component, accurate calculation can be quite complex. We can simplify the process by considering separately the inertial force arising from inertia and the viscous force arising from viscosity among the hydrodynamic forces acting on the submersible during fluid motion. Ignoring their mutual influence, it is feasible to calculate the inertial force and viscous force acting on the submersible separately.

The inertial force acting on the submersible in a fluid can be calculated using the following formula:

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \\ B_6 \end{bmatrix} = \begin{pmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} & \lambda_{14} & \lambda_{15} & \lambda_{16} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} & \lambda_{24} & \lambda_{25} & \lambda_{26} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} & \lambda_{34} & \lambda_{35} & \lambda_{36} \\ \lambda_{41} & \lambda_{12} & \lambda_{13} & \lambda_{44} & \lambda_{45} & \lambda_{46} \\ \lambda_{51} & \lambda_{22} & \lambda_{23} & \lambda_{54} & \lambda_{55} & \lambda_{56} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} & \lambda_{64} & \lambda_{65} & \lambda_{66} \end{pmatrix} * \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix} \tag{3}$$

Applying the theorems of moment of momentum and momentum, we have:

$$\begin{cases} -X_i f = \dot{B}_1 + qB_3 - rB_2 \\ -Y_i f = \dot{B}_2 + rB_3 - pB_2 \\ -Z_i f = \dot{B}_3 + pB_2 - qB_1 \\ -K_i f = \dot{B}_4 + (qB_2 - rB_5) + (vB_1 - wB_2) \\ -M_i f = \dot{B}_5 + (rB_4 - pB_6) + (wB_1 - uB_3) \\ -N_i f = \dot{B}_6 + (pB_5 - qB_4) + (uB_2 - vB_1) \end{cases} \tag{4}$$

The viscous force acting on the submersible in a fluid can be calculated using the following formula:

$$\begin{cases} X_{vf} = f_X(\mathrm{u,v,w,p,q,r}) \\ Y_{vf} = f_Y(\mathrm{u,v,w,p,q,r}) \\ Z_{vf} = f_Z(\mathrm{u,v,w,p,q,r}) \\ K_{vf} = f_K(\mathrm{u,v,w,p,q,r}) \\ M_{vf} = f_M(\mathrm{u,v,w,p,q,r}) \\ N_{vf} = f_N(\mathrm{u,v,w,p,q,r}) \end{cases} \tag{5}$$

The calculation of the viscous force (or drag force) in a specific direction is as follows:

$$F = \frac{1}{2} C_d \rho A v^2 \tag{6}$$

Where C_d is the drag coefficient, ρ is the density of seawater (kg/m^3), A is the cross-sectional area perpendicular to the direction of motion (m^2), and v is the velocity of the submarine.

In addition, due to the presence of ocean currents, we must also consider the propulsive force of the current:

$$F_{Propulsion} = A(\overrightarrow{V_{Current}} - \overrightarrow{V_{Submersible}})\rho \tag{7}$$

Where $F_{Propulsion}$ represents the propulsive force of the ocean current, A is the cross-sectional area perpendicular to the direction of motion (m^2), ρ is the density of seawater (kg/m^3), $V_{Current}$ is the velocity of the ocean current, and $V_{Submersible}$ is the velocity of the submersible.

Gravity is calculated as follows:

$$G = mg \tag{8}$$

Where m represents the mass of the submersible (kg) and g represents the acceleration due to gravity.

Buoyancy is calculated as follows:

$$F_{Buoyancy} = \rho V g \tag{9}$$

Where ρ is the density of seawater kg/m^3), V is the volume of the submersible in seawater, and g represents the acceleration due to gravity.

4.2 Environmental Model and Parameters

4.2.1 Environmental Parameters

To simplify the processing, we establish an environmental model for the ocean current environment where the submarine operates. This model approximates the ocean current environment as multiple cubes with a fixed side length. Within each cube, the seawater density, ocean current speed, viscous coefficient, water depth, and cross-sectional area perpendicular to the forward direction are considered uniform, given an appropriate cube side length. The specific parameters within this environmental model are outlined in **Table 2**.

Symbols	Definitions
ρ	seawater density
T	seawater temperature
S	seawater salinity
$V_{Current}$	ocean current speed
C_d	viscous coefficient
z	water depth
x, y	coordinate position
l	side length of the divided cube

Table 3: Defined Environmental Parameters

4.2.2 Source and Calculation of Parameters

We have access to terrain map information, seawater temperature information, and ocean current map information for the Ionian Sea. By physically calculating the parameters extracted from these sources, we can obtain the corresponding environmental parameters.

First, we identify some parameters in the Ionian Sea that can be considered constants. These parameters are assumed to be identical and unchanged throughout the entire sea area, as detailed in **Table 4**.

Parameters	Values
Temperature Coefficient α	$0.2 \times 10^{-3}\ ℃^{-1}$
Salinity Coefficient β	$0.78 \times 10^{-3} psu^{-1}$
Surface Salinity of the Ionian Sea S_0	$38\ psu$

Surface Density of the Ionian Sea ρ_0	$1.0234 \times 10^3 kg/m^3$

Table 4: Constant Parameters in the Ionian Sea Environment

For a given position (x, y, z) and a specified cube region with side length l, we can directly obtain the ocean current speed $V_{Current}$ from the ocean current map. Additionally, we can obtain the seawater temperature at the surface $T_{0(x,y)}$ for the (x, y) position using the seawater temperature information. However, the seawater density ρ, non-surface seawater temperature T, seawater salinity S, and drag coefficient C_d require further calculations.

The temperature of the water body T is related to the surface temperature of the seawater at the corresponding coordinates and the depth z of the water body. The temperature of a water body at a depth of z can be calculated using the following formula:

$$T_{x,y,z} = T_{0(x,y)} - \alpha z \tag{10}$$

Where $T_{x,y,z}$ represents the temperature of the water body at position (x, y) and depth z, $T_{0(x,y)}$ represents the surface temperature of the seawater at position (x, y), and α is the temperature coefficient. The value of $T_{0(x,y)}$ is extracted from the temperature distribution information of the sea area.

The salinity of the water body S is related to the surface salinity of the seawater in the corresponding sea area and the depth z of the water body. The salinity of a water body at a depth of z can be calculated using the following formula:

$$S_z = S_0 + \beta z \tag{11}$$

Where S_z represents the salinity of the water body at a depth of z, S_0 represents the surface salinity of the Ionian Sea, and β is the salinity coefficient.

The density of seawater ρ is related to the salinity S and temperature T of the seawater. Since both S and T are functions of depth z according to Equations (10) and (11), the density of seawater at a depth of z can be calculated using the following formula:

$$\rho_z = \rho_0[1 - \alpha(\mathrm{T} - T_0) + \beta(\mathrm{S} - S_0)] \tag{12}$$

Where ρ_0 is the surface density of the Ionian Sea, T_0 is the surface temperature, S_0 is the surface salinity, α is the temperature coefficient, and β is the salinity coefficient.

The drag coefficient C_d is positively correlated with the density of seawater ρ and the viscosity of seawater μ_{sw}. Specifically:

$$C_d = \mu_{sw}\rho \tag{13}$$

The viscosity of seawater μ_{sw} can be calculated using the following formula:

$$\mu_{sw} = \mu_w(1 + AS + BS^2) \tag{14}$$

Where μ_w is the viscosity of pure water, S is the salinity of the seawater, and A and B are coefficients related to the temperature T of the seawater. The value of S can be derived from Equation (11), and μ_w, A, and B can all be expressed as functions of the temperature T of the seawater:

$$\mu_w = 4.28 \times 10^{-5} + \frac{1}{0.157(T + 64.993)^2 - 91.296} \tag{15}$$

$$A = 2.592 \times 10^3 + 3.3 \times 10^{-5} T \tag{16}$$

$$B = 1.0675 \times 10^4 + 5.185 \times 10^{-5} T \tag{17}$$

By simultaneously solving equations (13) to (17), a relationship formula can be derived between the drag coefficient (C_d), seawater density (ρ), and seawater temperature (T):

$$C_d = \rho \times \left(4.28 \times 10^{-5} + \frac{1}{0.157(T + 64.993)^2 - 91.296}\right) \times (1.242 + 0.072T) \tag{18}$$

Based on the above parameters and equations (10), (11), (12), and (18), the required parameters of ρ, S, T, and C_d can be obtained from the environmental model, providing a complete set of model parameter data.

4.3 Program Structure

To simulate the motion of the submarine on a computer, the following adjustments are made to the aforementioned theory:

1) The continuous differential equations are discretized to obtain the difference equations for the model.

2) Classes for the submarine and the marine environment are constructed. The code structure for these classes includes functions to:

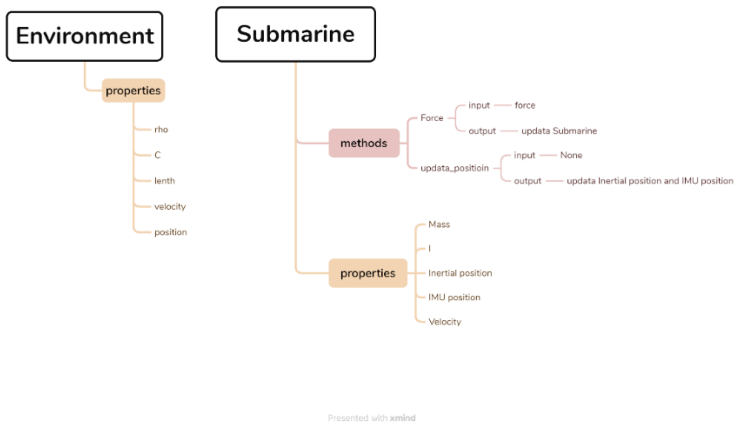

Figure 4: Schematic Diagram of Program Structure

Construct functions to obtain the submarine's forces based on the environment and its attitude, divide the continuous marine environment into discrete sections of a specified side length, and retrieve environmental attributes from ocean current maps, seabed terrain maps, and ocean temperature maps.

As illustrated in the figure:

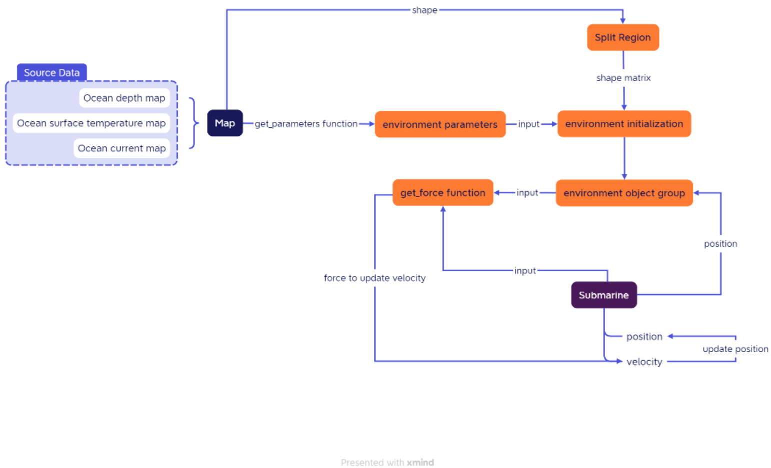

Figure 5: A relational graph of functions for obtaining environmental attributes

We divide the entire marine area into several discrete parallelepipeds, with the vertices of each parallelepiped serving as the coordinates for that specific section. Since these marine sections are small enough, it is assumed that their physical parameters are uniform. We proceed by reading the terrain maps, removing the land areas, resizing them according to the defined parallelepiped shape, and ultimately eliminating the portions located below the depth map. This allows us to accurately simulate the submarine's real motion in that region within the program.

3) With a time step of $\Delta t=1s$ and a simulation duration of 10,000s, the simulation program is executed, and the resulting data is output.

4.4 Model Verification

Through preliminary analysis, we believe that temperature and ocean current factors, as uncertainty factors, have a non-negligible impact on our prediction model. Next, we will control the variables and simulate the model considering or not considering various uncertainty factors using MATLAB. We will obtain predicted path diagrams under different scenarios and compare them with the actual situation images using the same initial parameters. Subjective observation of the differences in the images, combined with the average distance evaluation method, will demonstrate that considering these uncertainty factors provides a better fit in predicting the real path compared to ignoring them, thereby justifying the non-negligible impact of these uncertainty factors.

Here, we divide the specific situations of the submarine into three types for discussion: suspension, ascent, and descent. For each of these types, we have an actual path serving as a control group. We will simulate four scenarios for each type: (1) assuming the seawater is a uniform static fluid, ignoring temperature and ocean current factors; (2) considering only temperature factors; (3) considering only ocean current factors; and (4) considering both temperature and ocean current factors. After obtaining the predicted path images for the four scenarios using MATLAB, we will compare them with the actual path images and analyze the fit between the predicted and actual paths using the average distance evaluation method.

The simulated and actual paths of the submerged, ascending, and descending submersibles under four scenarios are shown in Figure 6.

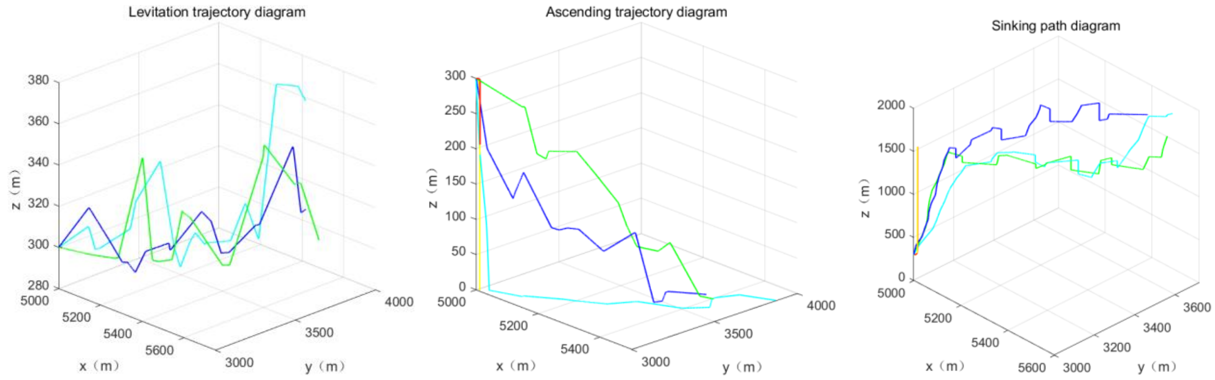

Figure 6: Simulated Paths of the Submerged, Ascending, and Descending Submersibles (Blue - Actual Situation; Green - All Factors Considered; Cyan - Only Ocean Current Considered; White - Only Temperature Considered; Red - No External Factors Considered)

The average distance evaluation criterion is used to evaluate the simulated paths based on the obtained four scenarios compared to the actual path. The evaluation image is shown in **Figure 7**. This criterion represents the average distance between the simulated path and the actual path at a given moment. The smaller the value, the closer it is to the actual path, indicating a higher fit for the simulated path.

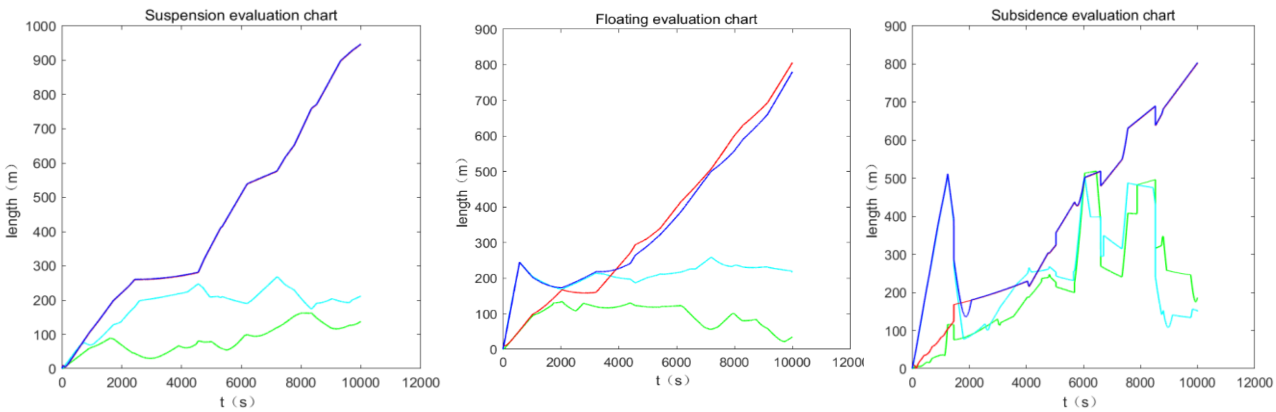

Figure 7: Average Distance Evaluation of the Simulated Paths of the Submerged, Ascending, and Descending Submersibles (Green - considering all factors; Cyan - considering only current factors; Red - considering only environmental factors; Blue - without considering external factors)

It should be noted that, in the case of suspension, the distance moved by the submersible is extremely small when temperature and ocean current factors are not considered, to the extent that the simulated path (i.e., the red simulated path line) is barely visible in the path diagram on the leftmost figure of **Figure 6**.

4.5 Conclusion

Through comparative analysis, it can be seen that temperature mainly affects the z-coordinate during the drifting process of the submarine, while ocean currents affect the x and y-coordinates. When the submarine sinks, due to the underwater terrain, the submarine's movement trajectory exhibits significant differences.

In summary, based on the comparison of intuitive simulation paths and real paths, as well as the graphical representation of average distance evaluation, it is easy to see that both temperature and ocean current factors have a very significant impact on the accuracy of our prediction model. Therefore, the submarine can periodically send water temperature information and ocean current information to the mother ship to reduce these uncertainties.

To achieve this, the submarine first needs to be equipped with temperature sensors to measure the temperature of the water in which it is located. These sensors can be deployed on the exterior of the submarine to directly contact and measure the surrounding water temperature. Secondly, to measure ocean current information, the submarine needs to be equipped with a current meter (also known as a flowmeter or flow sensor). This device can measure the speed and direction of water flow, thereby providing ocean current information. The submarine then requires a data processing and storage unit to receive data from the temperature sensor and current meter, and perform necessary processing and analysis. The processed data can be stored in the internal memory of the submarine for subsequent uploading to the mother ship. Finally, to send the processed data to the mother ship, the submarine needs to be equipped with an underwater acoustic communication system. This system utilizes sound waves for underwater communication and can upload data from within the submarine (including water temperature and ocean current information) to the mother ship. The underwater acoustic communication system typically includes a transmitter and a receiver. The submarine sends data through the transmitter, and the mother ship receives the data through the receiver.

5. Task2: Prepare

In order to add equipment and reduce uncertainties while considering financial constraints, we have selected the following types of equipment: first, sonar equipment for searching and locating the submarine; second, underwater drones for exploring the submarine's position; and third, searchlights for illuminating the seawater to aid in the search for the submarine.

Here, we have collected and selected nine devices and recorded relevant parameters as examples to illustrate and suggest how submarine companies should choose appropriate rescue equipment. The specific parameter information is shown in **Table 5** below:

No.	Detection Distance (m)	Price ($)	Speed (m/s)	Endurance (h)	Exploration Angle (°)	Device Type

1	36	702.83	-	12	10.5	Sonar
2	130	2007.98	-	12	15	Sonar
3	100	1099	2	2	100	Underwater Drone
4	91	139	-	12	8	Sonar
5	60	772.43	-	12	22	Sonar
6	60	111.2	-	4	30	Searchlight
7	25	799	3.5	2	164.6	Underwater Drone
8	100	1799	2.5	5	130	Underwater Drone
9	15	599	1.5	4	120	Underwater Drone

Table 5: Specific Parameter Information for Rescue Equipment

5.1 Calculating Weight Vectors Using the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP), also known as the system analysis method, is a qualitative and quantitative decision-making approach that combines both systematic and hierarchical elements. This method decomposes the elements related to the decision problem into multiple levels such as objectives, criteria, and alternatives, and then performs qualitative and quantitative analysis based on these levels. In our case, we have fewer evaluation indicators, so layering may not be entirely suitable. Instead, we will only use the weight vector calculation method from AHP to obtain the weights of each evaluation indicator for further processing.

We will set up only one level of indicators and decompose the decision problem into three levels. The topmost level is the objective level (M), which represents the key indicators for selecting the most suitable rescue equipment. The bottommost level is the alternative level, consisting of nine different rescue devices (P1, P2, P3, P4, P5, P6, P7, P8, P9). The middle level is the criterion level, including five indicators: detection distance (C1), price (C2), speed (C3), endurance (C4), and exploration angle (C5).

Constructing the Judgment Matrix (M-C): By pairwise comparison of the five elements (C1, C2, C3, C4, C5) in the criterion level, we obtain the pairwise comparison matrix.

M	C1	C2	C3	C4	C5
C1	1	1/3	2	2/3	1
C2	3	1	4	2	5/2
C3	1/2	1/4	1	2/3	1/2
C4	3/2	1/2	3/2	1	3/2
C5	1	2/5	2	2/3	1

By solving, we can obtain the eigenvalues of the judgment matrix (M-C). Using the formula $CI = \frac{\lambda - n}{n-1}$, we can calculate CI = 0.0134. Looking up the table with n = 5, we find RI = 1.12. Using the formula $CR = \frac{CI}{RI}$, we can solve for CR = 0.0119 < 0.1, which passes the consistency check. The resulting weight vector is

ω_0=(0.1509,0.3996,0.0951,0.1981,0.1562)^T.

Each value in the weight vector represents the corresponding weight for the five evaluation indicators.

5.2 TOPSIS Comprehensive Evaluation

After obtaining the weight vector ω_0, we can use the weighted TOPSIS algorithm to evaluate these nine rescue devices. TOPSIS is a commonly used comprehensive evaluation method. This method ranks evaluation objects based on their proximity to idealized targets, evaluating their relative advantages and disadvantages among existing objects. TOPSIS is particularly effective in multi-objective decision analysis and is also known as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).

The basic principle of TOPSIS is to rank evaluation objects based on their distances from the optimal solution and the worst solution. If an evaluation object is closest to the optimal solution and farthest from the worst solution, it is considered the best; otherwise, it is not considered optimal. Here, the "optimal solution" refers to the scenario where all evaluation indicators reach their optimal values, while the "worst solution" refers to the scenario where all evaluation indicators reach their worst values. After obtaining the weight vector ω_0 in Section 5.1, we can introduce the weights and perform a weighted TOPSIS analysis.

Based on Table 5, we can formulate the matrix of evaluation objects.

M	C1	C2	C3	C4	C5
P1	36	702.83	-	12	10.5
P2	130	2007.98	-	12	15
P3	100	1099	2	2	100
P4	91	139	-	12	8
P5	60	772.43	-	12	22
P6	60	111.2	-	4	30
P7	25	799	3.5	2	164.6
P8	100	1799	2.5	5	130
P9	15	599	1.5	4	120

We then obtain the relative closeness degree vector ψ_i, and by multiplying it with the weight vector ω_0, we can calculate the final evaluation score for each rescue device using the formula:

$$M_i = \psi_i \cdot \omega_0 \cdot 100 \tag{19}$$

Finally, we obtain the evaluation score vector M = (34.41, 69.86, 50.52, 26.42, 37.89, 11.75, 43.97, 77.00, 31.79). Each value in the evaluation score vector corresponds to the evaluation value of the nine different rescue devices. A higher evaluation value indicates a higher recommendation for the submarine company to purchase that rescue device.

Please note that this is just an illustrative example, and the specific situation may require further analysis. For example, if cost is not a significant concern but the rescue effectiveness of the rescue devices is crucial, the comparison matrix values for price (C2) can be adjusted relatively lower than other evaluation parameters in Section 5.1 before performing the subsequent calculations.

6. Task3: Search

6.1 Searching for Deployment Points

To find a lost submarine, we can simulate its drifting route in the ocean after losing contact and power in our program. Since it takes time for rescue ships to arrive, they need to be dispatched to deployment points along the route (rather than the exact point of loss of contact) to initiate the search.

Given the displacement function of the lost submarine from the point of loss of contact as the origin, denoted as $\vec{r} = f(t)$, and the location of the rescue ship at the time of loss of contact as $\overrightarrow{R'}$, the deployment points for the search are determined by the following requirements:

$$\vec{r}(t) = \overrightarrow{R'} + \vec{R}(t) \tag{26}$$

6.2 Search Strategy

Due to the uncertainties in the marine environment, the probabilities of finding the submarine in each searched area change as the search progresses. Therefore, we need to formulate new search plans based on these changing probabilities. In developing the search strategy, we innovatively incorporate optimization algorithms such as ant colony and simulated annealing, using computer-assisted methods to choose the search paths.

In the program, we divide the entire sea area into smaller regions and assign physical attributes to them. These attributes directly influence the future route of the powerless submarine. However, the physical attributes in the sea area are highly uncertain, and searching in any direction involves different probabilities of finding the submarine. Inspired by particle swarm optimization, we create a sufficient number of virtual submarines (typically 1000) in the computer, all with the same initial position as the rescue ship. We assign different familiarities (such as mass, speed, angular velocity, etc.) to these virtual submarines within a reasonable range to simulate possible parameter variations and prediction errors after the submarine loses contact.

These virtual submarines will simulate drifting in the program, and we can observe distinct "trends" in their trajectories. Most of the lines converge and point to specific directions, while a few stray away. These lines represent probabilities, and denser areas indicate a higher likelihood of the lost submarine drifting in that direction, thus increasing the probability of finding it. However, these lines only represent trends and may lead us to locally optimal probabilities.

Drawing inspiration from simulated annealing algorithms, we consider the ratio of submarines in a particular direction to the total number as the probability. For each simulation result, we use the Boltzmann distribution law to selectively accept or reject it, gradually reducing the temperature and the randomness of the submarines' initial attributes until an optimal route is identified.

The following figure is the flowchart of the search strategy:

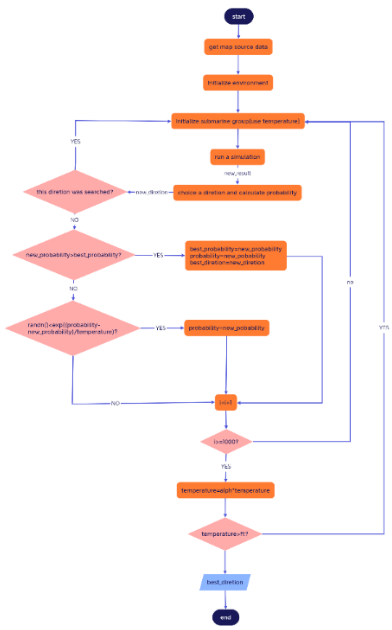

Figure 8: Flowchart of Search Strategy

The following figure is the trajectory diagram of the submarine in a single cycle:

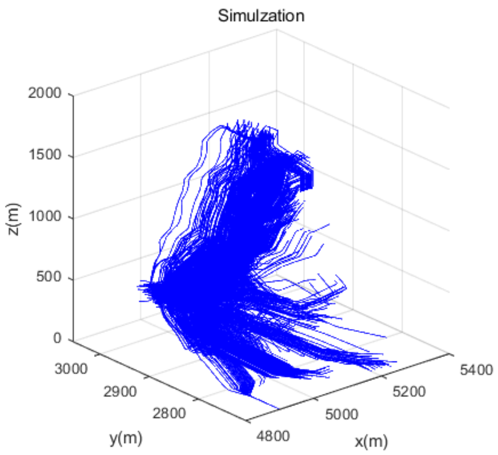

Figure 9: Trajectories of Submarines in a Single Cycle

At this point, we have identified the best path for the search.

7. Task4: Extrapolate

7.1 Caribbean Sea

To apply our model to the Caribbean Sea, we only need to change our map reference points and import the seabed topography map, sea surface temperature map, and ocean current map of the Caribbean Sea. Our simulation results are as follows:

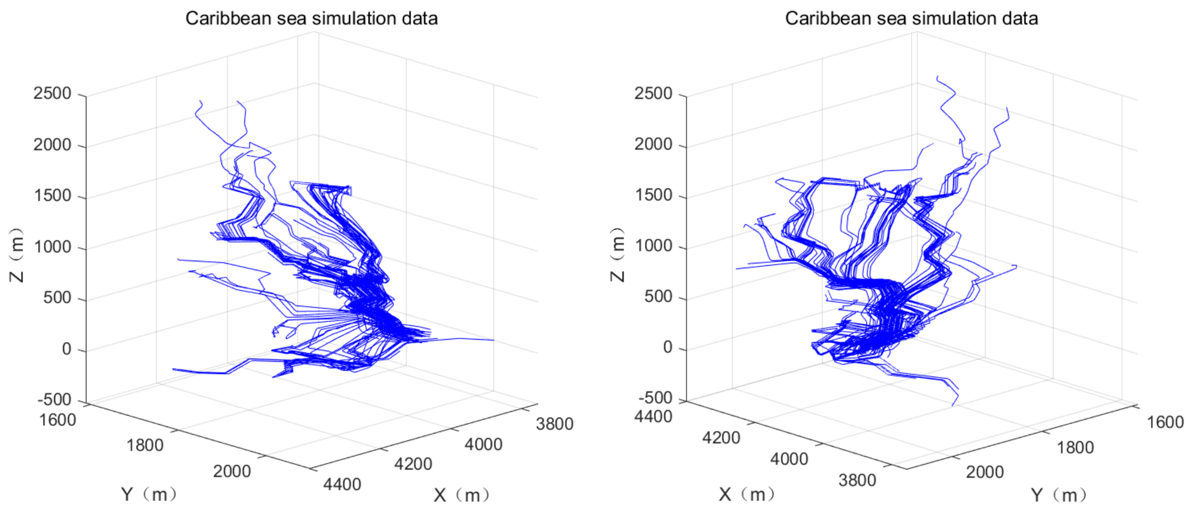

Figure 10: Submarine Trajectory Diagram in the Caribbean Sea

7.2 Multi-Submarine Search

In our model, we have simulated the movement of a large number of submarines in similar waters without power. We can allow each search and rescue vessel to search according to their own optimal solution in that sea area. However, the search paths between submarines are prone to overlap, which is very inefficient (in our program, we also prevent submarines from backtracking and searching areas that have already been searched during the search). Therefore, we need another search method to solve the problem of multi-submarine search.

The search equipment itself has the ability to resist ocean current movement and can freely traverse the sea area. We still discretely divide the sea area into corresponding small sea areas. Given the need to balance both time and probability during the search, we use a combination of Bayesian search, particle swarm optimization, annealing algorithm, and depth-first search (DFS) for the search.

Our submarines will mark the sea areas that have been searched. When the search strategy algorithm calculates a result that is a marked sea area, we will choose the second most probable direction as the new search direction. If the second choice is also a marked sea area, we will continue to choose the next best option until the entire sea area has been searched.

The flowchart is as follows:

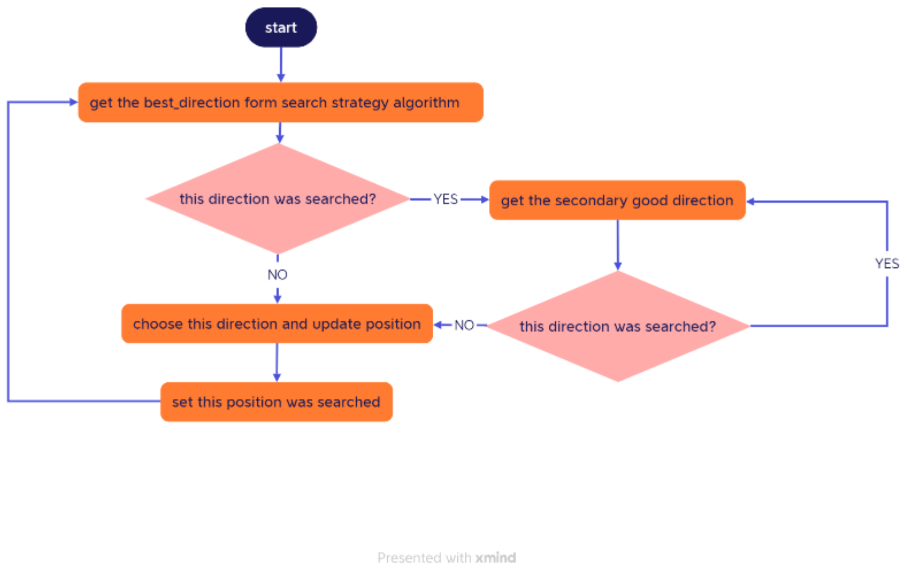

Figure 11: The flowchart of Multi-Submarine Search

The reason for choosing the depth-first approach: Because the search and rescue model is a differential equation model, the longer the time, the greater the prediction error of the program, and the probability starts to spread spatially. Therefore, the search and rescue efficiency is higher when the probability density near the loss point is still relatively high in the early stage of the search and rescue. Choosing to search along the highest probability route can increase the chance of finding the target in a short time compared to other directions, making it a better solution to this problem.

8. Sensitivity Analysis

Using -500kg as a reference, a sensitivity analysis of mass changes near the equilibrium mass on the average distance of the trajectory was conducted. 0kg represents the equilibrium mass, and the generated image is shown below:

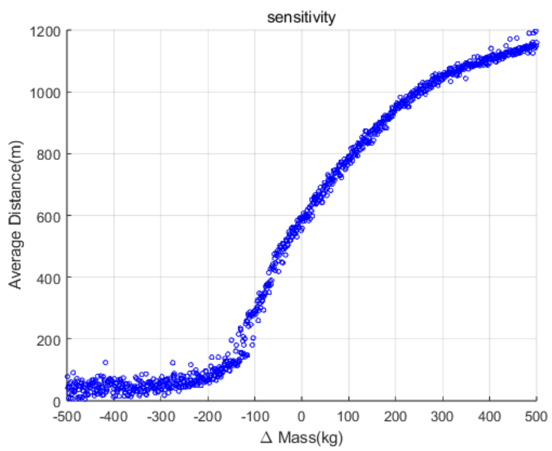

Figure 12: Sensitivity Analysis of Mass Changes on the Average Distance of the Trajectory

It can be seen that changes in mass have a significant impact on the degree of deviation between the two trajectories, especially near the equilibrium position. This is because slight changes in the mass of the submersible at the equilibrium position can create a tendency to move in the positive or negative direction along the z-axis in the water, which in turn affects whether we should ultimately conduct the search and rescue operation on the seabed, at the sea surface, or in the middle of the water column. Therefore, collecting information on the mass of the submarine before it went missing is quite important.

Using -20m/s as a reference, the sensitivity analysis of the initial velocity at the time of loss on the average distance of the trajectory is as follows:

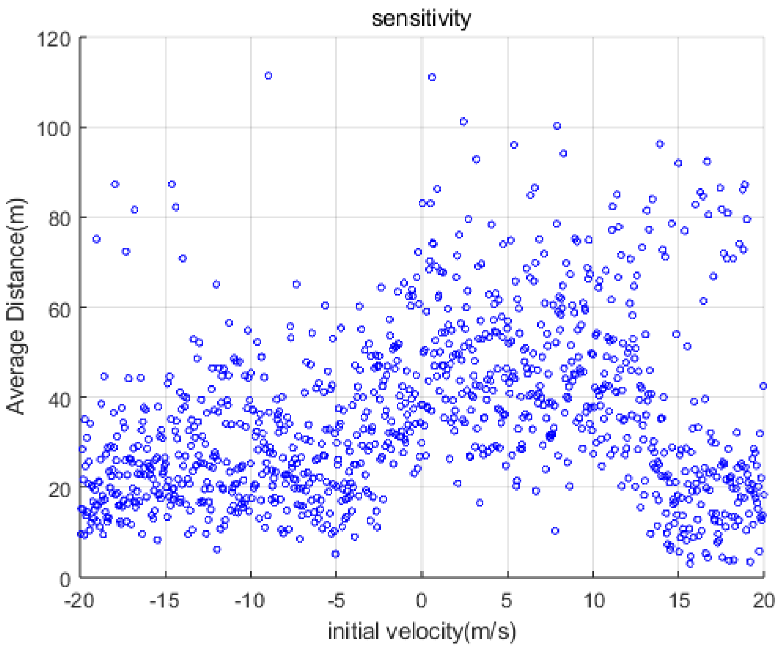

Figure 13: Sensitivity Analysis of Initial Velocity on the Average Distance of the Trajectory

It can be seen that the data is relatively scattered, and there is no obvious relationship between the two. However, it can be observed that the impact of initial velocity on the error is concentrated between 10-60m, which is the range that most search and rescue equipment can cover. In addition, the majority of the errors are below 100m, with only a few pieces of search and rescue equipment capable of operating at this distance. Therefore, initial velocity information is not as essential as one might imagine. This is because the resistance of seawater is significant, causing the submarine to decelerate rapidly until it approaches the flow velocity of the environment.

For environmental variables, conducting a sensitivity analysis is not feasible due to the enormous amount of environmental data generated by a single simulation (in our case, approximately 600*800*100 environmental objects are created).

9. Strengths and Weaknesses

9.1 Strengths

1)The model accurately models the six degrees of freedom movement of the submarine, considering various environmental factors such as seawater temperature, salinity, and flow rate that affect the submarine's movement. This enhances the model's accuracy, making the simulation results closer to actual situations.

2)The model takes into account various practical scenarios, including the influence of uncertain factors, providing a solid foundation for subsequent search missions. Meanwhile, the comprehensive evaluation method based on Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) provides effective decision support for the selection and purchase of rescue equipment.

3)The model not only considers the submarine's motion model but also encompasses multiple aspects such as rescue equipment selection strategies and search strategies, forming a complete deep-sea exploration safety system and emergency response plan.

9.2 Weaknesses

1)Although the model considers various environmental factors, it still relies on some idealized assumptions, such as selecting a relatively stable reference frame to approximate the absolute inertial reference frame. This could lead to inaccuracies in the model under certain extreme conditions.

2)he model's involvement of multiple aspects and factors results in its relative complexity. This could increase computation time and difficulty, which may not be conducive to real-time decision-making and emergency response.

3)To maintain the model's accuracy and practicality, a significant amount of actual data is required to support its operation and validation. This could increase the difficulty and cost of data collection and processing.

10. Memo

To: Greek Government

Subject: Memo - Deep Sea Exploration Safety Measures and Emergency Preparedness

Dear Sir/Adam

I am writing to provide a summary of a research paper that focuses on safety measures and emergency preparedness in deep-sea exploration activities, particularly in relation to the movement model of submersibles, the selection strategy for rescue equipment, and search strategies. This research paper aims to address crucial aspects of deep-sea exploration and provide valuable insights for future expeditions and studies.

The research paper begins by establishing an accurate hydrodynamic model that encompasses the six degrees of freedom (DOF) movement of submersibles in three-dimensional space. This model serves as a solid foundation for subsequent search missions by providing precise predictions of submersible movements in the deep sea.

In the process of developing the model, the research paper considers environmental factors such as seawater temperature, salinity, and flow velocity, incorporating them into the model to enhance its accuracy and practicality. Additionally, the paper conducts controlled simulations to assess the impact of uncertainties on the model, further validating its robustness.

Regarding search missions, the paper proposes a comprehensive evaluation method based on the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm. This method first employs AHP to determine the weights of various evaluation criteria and then utilizes the TOPSIS algorithm to rank and select different types of rescue equipment. Through this approach, the paper successfully provides a purchasing recommendation for rescue equipment.

Furthermore, in the search strategy, the paper introduces an innovative approach by incorporating ant colony optimization and simulated annealing algorithms, which are widely used in optimization algorithms, to assist in selecting search paths using computer assistance. This algorithm helps identify the optimal search route, thereby enhancing the efficiency of submersible searches.

In the context of practical applications, the established model and search strategy were simulated and applied to deep-sea exploration missions in the Caribbean Sea. By comparing actual search results with model predictions, the effectiveness and practicality of the proposed methods were validated. Additionally, the paper employs a depth-first algorithm to optimize collaborative search strategies in scenarios involving multiple submarines, providing valuable insights for future collaborative submersible tasks.

In conclusion, this research paper primarily focuses on establishing an accurate submersible movement model, proposing effective search strategies, and introducing a comprehensive evaluation method. Through these efforts, the paper addresses a series of critical issues in deep-sea exploration missions, providing valuable references for future deep-sea expeditions and research.

Keywords: six degrees of freedom movement model, Analytic Hierarchy Process, TOPSIS algorithm, simulated annealing optimization algorithm, collaborative search strategy, depth-first algorithm

I hope this summary provides a concise overview of the research paper's findings and its implications for deep-sea exploration safety and emergency preparedness. The insights presented in this report can serve as a valuable resource for the Greek government in evaluating and approving deep-sea exploration projects, ensuring the safety of participants and the success of these endeavors.

If you require any further information or have any specific questions, please do not hesitate to contact me. Thank you for your attention to this matter.

Yours sincerely,

Sincerely Students

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Regular Paper Minghui Wang1,Yongquan Yu, Bi Zeng and Wei Lin Faculty of Computer Science, Guangdong University of Technology, China

Report on Use of AI:

1. OpenAI ChatGPT (Nov 5, 2023 version, ChatGPT-4)
Query1:<Translate Chinese papers to English papers>
Output:<English papers >