Research on deep-sea submarine distress positioning prediction based on hydrodynamics and numerical simulation techniques

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Abstract. The purpose of this paper is to study the problem of positioning prediction of deep-sea submarines after distress. Firstly, the kinematic equations of a deep-sea submarine in seawater are established, and the motion characteristics of a deep-sea submarine under the action of water current are analysed. Subsequently, a computational model of the current velocity in the Mediterranean Sea was established, and the positioning prediction of the submarine was carried out based on this computational model. In addition, the article proposes a search device selection method based on decision tree and TOPSIS algorithm, and a search path planning method based on happiness search algorithm. Ultimately, the research results show that the method is effective and reliable in submarine distress positioning prediction.

Keywords: Deep-sea submarine; Distress localisation; Hydrodynamics; Numerical modelling; Search equipment; Search paths.

1. Introduction

1.1. Background

Deep-sea submersibles constitute critical apparatuses for scientific research and exploration in marine abysses. Specifically, operational deep-diving manned submersibles have emerged as pivotal vehicles for underwater exploration, furnishing robust technical support to the advancement of the international deep-sea sector1. Nevertheless, the unique attributes of the marine abyssal environment necessitate that operators remain within an entirely sealed environment. In such a situation, the occurrence of an incident significantly complicates rescue efforts and elevates the likelihood of substantial casualties. A poignant illustration of this is the Titan submersible mishap in June 2023, wherein isolation from external communication combined with the profound high-pressure conditions of the deep sea precipitated the nearly instantaneous demise of the vessel's crew2. Hence, the enhancement and refinement of external rescue methodologies have been underscored across the board in the development of contemporary submersibles.

Currently, the Greek submersible fabricator, Maritime Cruises Mini-Submersibles (MCMS), aspires to deploy its submersibles for conducting underwater expeditions in the Ionian Sea, aiming to uncover shipwrecks. Nonetheless, ensuring the safety of its manned submersibles presents a formidable challenge. These submersibles are susceptible to signal disruptions or malfunctions when distanced excessively from the primary vessel, thereby endangering passenger safety. Consequently, it is imperative for MCMS's manned submersibles to possess the capability for both pre and post expedition localization and to address potential contingencies that may emerge during these sub-aqueous voyages in the Ionian Sea.

The aim of this paper is to investigate how to accurately predict the position of a deep-sea submarine in distress for effective search and rescue.

1.2. Literature Review

In the domain of maritime navigation and rescue operations, the intricacies of locating lost submersibles have garnered substantial attention within the academic community. Meng et al in 2018 conducted a pivotal study on the drift trajectory modeling of non-powered ships at sea, meticulously

analyzing the impact of wind forces and oceanic currents on the adrift vessel's movement[1]. Their research underscores the significant influence of sea surface wind fields and ocean currents on maritime drift patterns. The trajectory model they developed offers a robust framework not only for understanding the drift behavior of ships but also holds potential applicability in predicting the motion of submersibles when subjected to oceanic forces[2,3]. Carneiro introduced a novel proposition for the employment of satellite communications as a solution to the limitations of conventional communication methodologies in establishing contact with submerged submersibles. It solves the problem of the failure of traditional means of communication and better provides accuracy and efficiency for the positioning of submersibles.

The challenge of rescue operations for lost submersibles has been a recurrent theme in maritime research literature. Early in 1972, Joseph advocated for the integration of standardized safety features on submersibles to enhance the efficacy of search and rescue operations[4-6]. Furthermore, Joseph emphasized the strategic deployment of helicopters for the swift dis-patch of a Search and Rescue Submersible (SARS) system, highlighting the critical role of rapid response mechanisms in maritime rescue scenarios[7-10].

2. Location Prediction Model of a Submersible in the Ocean

The flow of the study is shown in Figure 1.

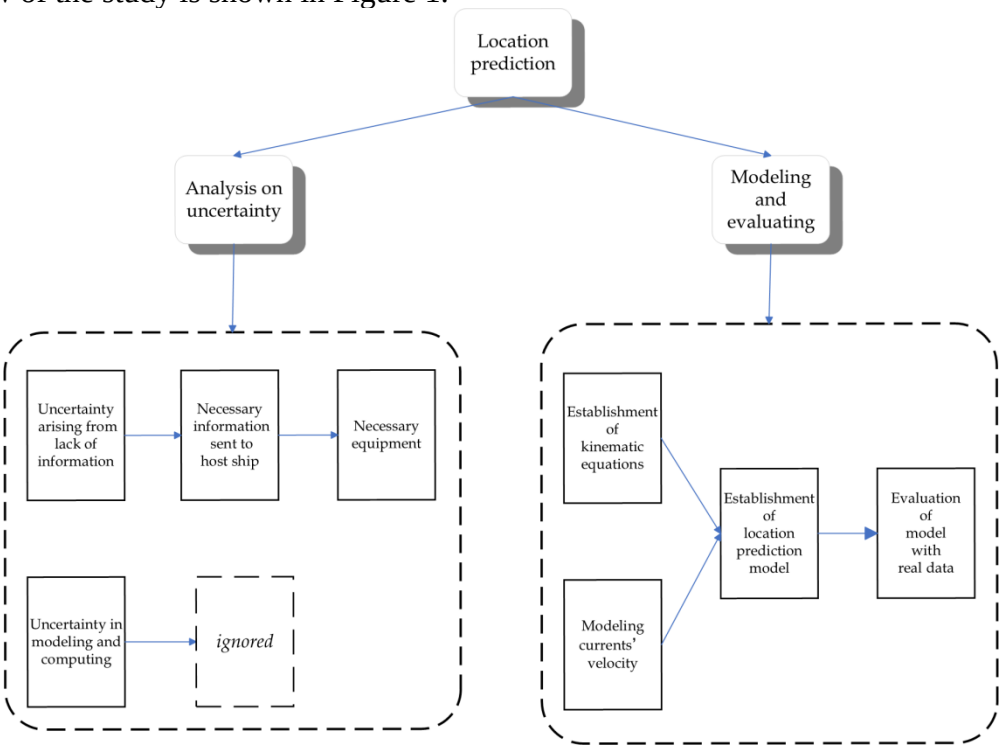


Figure 1. The flow of the study

2.1. Establishment of Kinematic Equations for Submersibles in the Ocean

2.1.1 Force Analysis of a Submersible

To elucidate the dynamics of a submersible's spatial trajectory over time, it is imperative to formulate its equations of motion. Subsequently, assessing the submersible's velocity under varying oceanic conditions necessitates consideration of the effects exerted by underwater currents, thermal variations, and other marine environmental influences. To abstracting and stream-lining the analysis of forces acting upon the submersible, a three-dimensional coordinate system, delineated by the x, y and z axes, is established, wherein the positive directions are denoted by x_+, y_+, z_+(Figure 2).

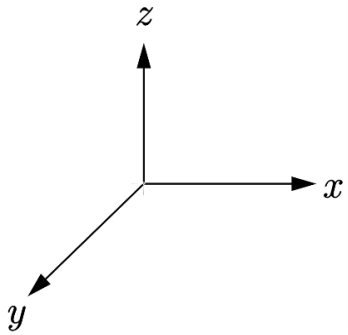


Figure 2. Coordinate (geometry)

In the context of submersible operations within aquatic environments, the force exerted on the submersible mainly comes from the force of earth gravity, $\overrightarrow{G_s}$, and water flow. According to Archimedes' principle, submersibles are subject to upward buoyancy, denoted as $\vec{F}_b$, perpendicular to the surface of the water. Furthermore, according to the findings of Meng et al., a submersible navigating through oceanic waters encounters an additional force on the x axis, $\overrightarrow{F_w}$, attributed to the thrust generated by the oceanic currents against the submersible's structure. The force structure is shown below(Figure 3):

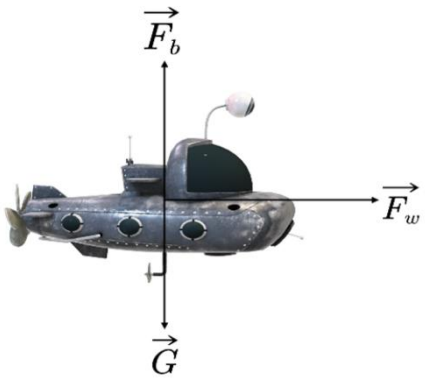


Figure 3. The force structure

According to the relationship between the gravity of seawater and the density of seawater ρ_w, the volume of discharged water V_s, and the acceleration of gravity, buoyant force can be obtained:

$$\vec{F}_b = \rho_w \cdot \vec{g} \cdot V_s \tag{1}$$

According to Meng et al., the thrust can be defined by the following expression:

$$\overrightarrow{F_w} = \frac{1}{2} \cdot \rho_w \cdot C_s \cdot A_s \cdot |\overrightarrow{v_{rw}}| \cdot \overrightarrow{v_{rw}} \tag{2}$$

where C_s is the drag coefficient, which is related to the submersible. A_s is the surface area of the side of the submersible, and $\overrightarrow{v_{rm}}$ is the relative velocity of the submersible, $\overrightarrow{v_s}$, with respect to the velocity of the current, $\overrightarrow{v_w}$, as defined by the following expression:

$$\overrightarrow{v_{rm}} = |\overrightarrow{v_s} - \overrightarrow{v_w}| \tag{3}$$

2.1.2 Kinematic Modeling of Submersibles

According to Newton's second law, the acceleration a of an object is directly proportional to the combined external force $\Sigma\vec{F}$ acting on it and inversely proportional to its mass m_s.

$$\sum \vec{F} = \mathrm{am_s} \tag{4}$$

Based on the analysis of the combined external force on the submersible, we can model the kinematics of the submersible. The submersible's own acceleration can be represented by a

differential equation for its velocity versus time, and therefore the kinematics of the submersible underwater are modeled as:

$$\overrightarrow{F_w} + \vec{G} + \overrightarrow{F_b} = m_s \cdot \left(\frac{\mathrm{d}v_s}{\mathrm{d}t} + a_c\right) \tag{5}$$

In this equation, a_c refers to the Coriolis force, which is due to the acceleration of the Earth's rotation. Nevertheless, given the relatively diminutive magnitude of the Coriolis force11, its impact can be deemed negligible within the scope of this analysis. Consequently, the kinematic model under consideration is formulated as follows:

$$\overrightarrow{F_w} + \vec{G} + \overrightarrow{F_b} = m_s \cdot \frac{\mathrm{d}v_s}{\mathrm{d}t} \tag{6}$$

2.2. Modeling of Current Velocity in the Ionian Sea Without the Influence of Topographic Factors

2.2.1 Overview of Current Velocity Calculation Model

Ocean currents affect the movement of a submersible underwater, so modeling is needed to calculate the velocity of ocean currents at different depths. Ocean currents are driven by tides, winds, and water density in nature12, so in a completely flat ocean a current with a horizontal velocity direction would be formed, defined as v_o, but seafloor topography creates a velocity component that distinguishes the current from the horizontal direction which would be defined as v_e.

$$v_w = v_o + v_e \tag{7}$$

However, in this section, we focus on the velocity of ocean currents in the absence of topographic factors. The main goal of this section is to develop a model that has a relationship between the position of the coordinates and the current velocity v_o of the ocean currents in the Ionian Sea, as shown in the following figure 4:

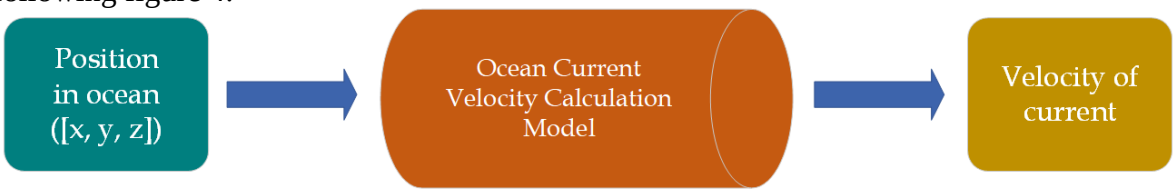


Figure 4. Work flow of current velocity model

2.2.2 Analysis of Ocean Currents in the Ionian Sea Area

The circulation patterns within the Ionian Sea are principally governed by the Mediterranean Current System (MCS), which originates from the Atlantic Ocean, traversing through the Strait of Gibraltar into the Mediterranean Sea, before being channeled through the MCS into the Ionian Sea13. Consequently, the predominant flow direction of currents within the Ionian Sea is from west to east. As the oceanic current navigates through the Ionian Sea, it encounters regions of shallow depth in the northern and southern expanses of the sea, coupled with areas characterized by reduced salinity. Guided by the principle of diffusion, these factors collectively facilitate the current's bifurcation towards the north and south14, which results in the direction of the ocean current as shown in the following figure 5.

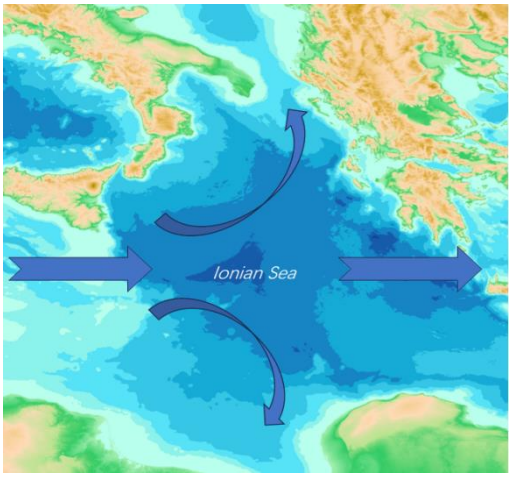


Figure 5. Direction of currents in Ionian Sea

2.2.3 Establishment of the velocity equation for ocean currents

It is observed that the current direction distribution agrees with the gradient vector distribution of the hyperbolic function, so the hyperbolic function is used to fit the current velocity v_o, thus obtain the equation:

$$v_o = \frac{\mathrm{d}\vec{x}}{\mathrm{d}t} = [\mathrm{sigmoid}(h_0)] \cdot \nabla f(\vec{x}) + \delta\overrightarrow{e_x} \tag{8}$$

Where Δh is the depth of the coordinate position from the sea surface, and h_0 is the function between the total depth of the sea and Δh. $\vec{x}$ is the displacement vector, and $\delta\overrightarrow{e_x}$ is the error term of the equation, and this item is not taken into account in the calculation. The equation about $\vec{x}$ can be defined as follows:

$$f(\vec{x}) = <\vec{c}, [x^2, y^2, 1]>^{\frac{1}{2}} \tag{9}$$

where $\vec{c} = [a, b, c]^T$ is the parameter vector. Solving equation gives:

$$\overrightarrow{v_o} = [\mathrm{sigmoid}(h_0)] \cdot \nabla f(x, y) = \left[\frac{ax}{\sqrt{c+ax^2+by^2}}, \frac{by}{\sqrt{c+ax^2+by^2}}, 0\right] \tag{10}$$

where a, b, c are relevant parameters of the hyperbolic function, which is the current velocity calculation model over position coordinate (x, y, z).

2.2.4 Calculation of Ocean Currents Model

By using the real ocean characteristics data from the Ionian Sea, the values of the parameters a, b, and c of the hyperbolic function are found to be 600, 360 and 100, respectively. Substituting the values of these parameters into Equation obtains the gradient heat map of $\nabla f(x, y)$ in the sea surface, which is the velocity of the surface water $v_o s$(Figure 6).

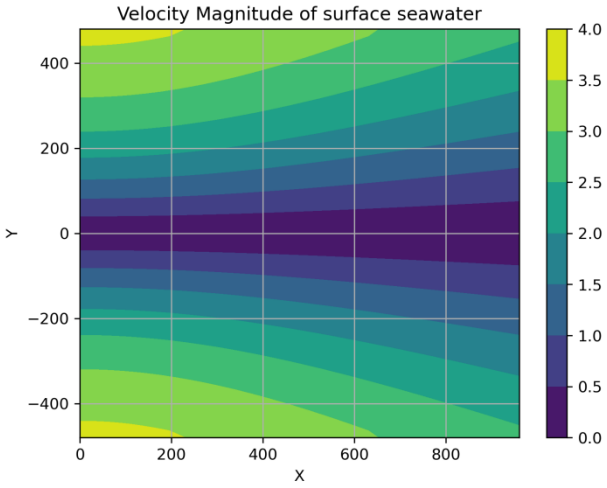


Figure 6. the gradient heat map

Projecting $v_o s$ according to water depth over the entire range of seawater depths, based on the actual flow rate data, obtains:

$$v_o = [2 \cdot \text{sigmoid}(h_0) - 1] \cdot v_{os} \tag{11}$$

where

$$\text{sigmoid}(h_0) = \frac{1}{1+e^{-h_0}} \tag{12}$$

where

$$h_0 = \frac{4(z+|h_d|)}{|h_d|} \tag{13}$$

After generating v_o at all depths, the results are shown below(Figure 7).

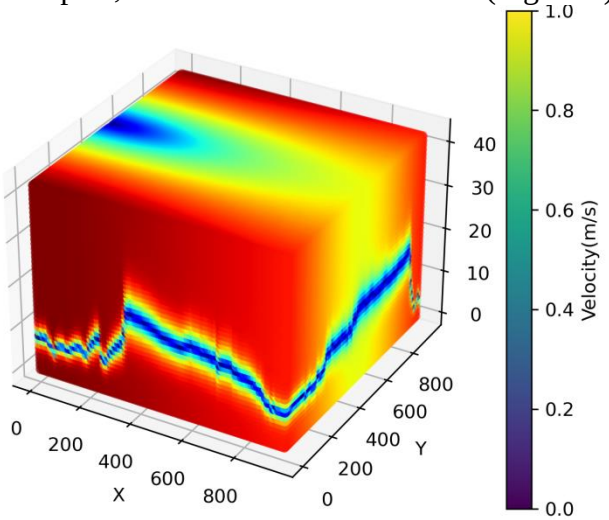


Figure 7. 3D Scatter Plot of Ocean Water Velocity

2.3. Solution of the Location Prediction Model in Ionian Sea

From the kinematic analysis, it can be concluded that in order to obtain the speed of the submersible, it is necessary to know the density of seawater ρ_w. According to the international standard seawater density equation, EOS-80 (Equation of State 1980), density of seawater is related to seawater temperature, salinity and seawater depth as follows:

$$\rho(S,T,D) = \rho_0 + (A(T) + B(T)D \times 0.1 + C(T)(D \times 0.1)^2)S + D(T)/S^{3/2} + E(T)S^2 \tag{14}$$

In this equation, $\rho(S,T,D)$ is the density of seawater(kg/m^3), S is salinity(psu), T is temperature($^\circ C$), D is depth(m),

Taking the average seawater density at the average temperatures of January, April, August and December in the Ionian Sea, the variation of density ρ_w with depth h was obtained in accordance with the following equation:

$$\rho_w = 0.000450 \cdot h + 1027.048931 \tag{15}$$

We use a numerical simulation model to construct the drifting trajectory at future moments given the initial position $x_i nit$, initial velocity $v_s - init$, and submersible density ρ_s. In order to show its trajectory better, we have taken the method of controlling variables by controlling the y-value constant (as shown in Fig. 19) and x-value constant (as shown in Figure. 8), and the results obtained are as follows:

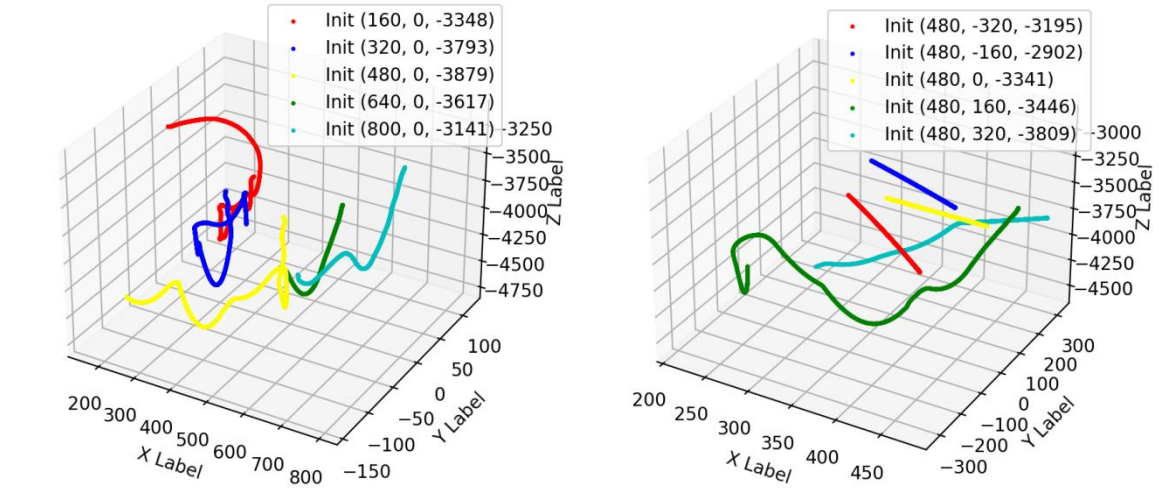


Figure 8. Prediction of drift trajectories controlling x-coordinates

3. Conclusion

This paper addresses the problem of predicting the positioning of a deep-sea submarine in distress and proposes a solution based on hydrodynamics and numerical simulation techniques. By establishing the kinematics equation of deep-sea submarine, the influence of water current on the submarine's movement is analysed, and the calculation model of the flow velocity in the Mediterranean Sea is constructed. On this basis, the article also proposes the selection of search equipment and the planning method of search path. The experimental results verify the effectiveness of the method, which provides important technical support for the search and rescue of deep-sea submarines in distress.

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