Research on High-Precision Positioning Technology for Deep-Sea Submersibles Based on Kalman Filtering

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Abstract. As an important tool for deep-sea missions, the position precision of the submersible is directly related to the success of the mission and the safety of deep-sea operations. High-precision positioning technology is urgently needed for deep-sea exploration to cope with the challenges of complex ocean currents, uneven seawater density and complex topography. Based on the Kalman filter method and fitting algorithm, a prediction model of submersible position in deep sea is established considering whether the submersible can keep communication with the main ship or not. In order to make the prediction model more convenient to use and more accurate. In this paper, the 3D coordinate system used in the prediction model is given, and the force acting on the submersible is analyzed. In addition, this paper also gives the uncertainty factors that affect the prediction model, and proposes that special equipment can be added to the submersible to reduce the interference of uncertainty factors.

Keywords: Kalman filter model, high-precision positioning technology, fitting the algorithm, uncertainties in the oceans, equipment held by the submersible

1. Introduction

The manned submersible is a kind of submersible device with underwater observation and operation ability, which can be used as a diver's underwater operations base and as a powerful tool for exploring the ocean depths. As the frontier of exploring the unknown world, deep-sea exploration requires high-precision positioning technology. However, deep submersibles are confronted with many challenges, such as complex and changeable ocean currents, the non-uniform density of seawater, and complex submarine topography. In practical applications, submersibles also run the risk of losing communication with the host ship and creating mechanical defects. At present, the traditional positioning methods can not meet the current accuracy requirements. Therefore, how to overcome the influence of the above factors effectively and improve the positioning accuracy and prediction reliability of the submersible has become an important research topic.

This study begins to use the Kalman filtering method. Kalman filter is an optimization algorithm for estimating the state of uncertain dynamic systems, which is widely used in trajectory prediction, data processing, and other fields. For example: parameter identification for ship mathematical model[1], flight target trajectory prediction [2], and dynamic geological model guidance [3], many studies are also based on the traditional Kalman filter based on innovation, the use of polynomial Kalman filter based on ship trajectory prediction [4], improved switching Kalman filter for bearing fault feature extraction [5]. Kalman filtering performs two stages: The prediction step (prediction stage) predicts the state of the current moment based on the dynamic model of the system and the estimation of the previous state. The other one is the update step (update stage). After receiving the measured data, the Kalman filter will combine the predicted state and the actual measured value to correct the state estimate by weighted average, to obtain a more accurate state estimate, and the Kalman filter will automatically adjust the weight according to the reliability of the measured data[6-7]. In addition, the data for this study came from earth.nullschool.net.

The coordinate system is established by taking the coordinates of the submersible as coordinate origin O. This study models the submersible in three directions of x, y, and z respectively, and discuss whether the submersible keeps communication with the main ship and whether there are mechanical

defects. Using the position information of the submersible as the measurement data, the Kalman filter method is used to update the data to obtain a more accurate state estimation, namely the position data of the submersible. In the case of communication loss, this study uses the fitting algorithm to fit the data before communication loss and use the predicted subsequent data as measurement data.

2. Establishment of the coordinate system and deep submersible force analysis

2.1. Create 3D Coordinate System

With the submarine as the coordinate origin O, x, and y axes are established along the latitude line and longitude line respectively. The positive direction of the x-axis is the direction of increasing longitude along the latitude line, the positive direction of the direction is the direction of increasing latitude along the longitude line, and the positive direction of the z-axis is the direction perpendicular to the seaplane and pointing to the center of the Earth. A three-dimensional coordinate system O(X, Y, Z) is established, as shown in Figure 1: The three-dimensional coordinate system diagram is shown.

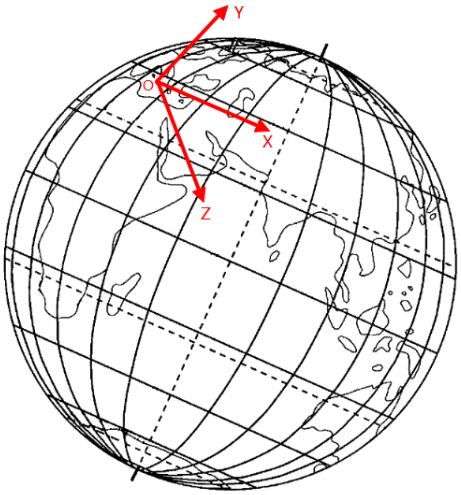


Figure 1. 3D Coordination System

2.2. Force analysis of submersible

2.2.1 Gravity

The expression of gravity on the submersible is:

$$G = mg \tag{1}$$

Where m is the mass of the submersible in the water.

2.2.2 Buoyancy force

The buoyancy force of the submersible is expressed as:

$$F_f = \rho g V \tag{2}$$

Where, ρ is the density of the submersible, g is the gravitational acceleration constant, and V is the volume of the submersible.

2.2.3 Viscous hydrodynamic force

The hydrodynamic characteristics and magnitude are related to the geometrical shape of the carrier, the motion state of the carrier, the nature of the flow field, the control factors, and so on. For a submersible, its shape structure has been determined after completion, so it is unnecessary to consider the influence of geometric shape on the hydrodynamic force in this paper. The properties of the flow field can be characterized by the Reynolds number, Frode number, and other non-dimensional

numbers, but the effect of the Frode number can be ignored when the submersible is moving in the deep sea, and the effect of the Reynolds number can also be ignored because the speed of the submersible changes little during the maneuvering process. It is generally believed that the submersible works in an infinite flow field, so the viscous hydrodynamic force is only related to the motion of the submersible, so the viscous hydrodynamic force can be expressed as the following function:

$$f = f(v_x, v_y, v_z) \tag{3}$$

Where v_x represents the speed of the submersible moving in the X-axis direction v_y, v_y represents the speed of the submersible moving in the Y-axis direction, and vz represents the speed of the submersible moving in the Z-axis direction.

2.2.4 Inertial hydrodynamic force

Submersible in the fluid to do variable speed movement, the submersible to change its speed at the same time must apply force on the surrounding fluid particles, so that they overcome the inertia to do variable speed movement, because of the inertia of the fluid particles, so the fluid particles on the object's reaction force constitute this resistance, so-called fluid inertia resistance. The inertial resistance of the fluid is proportional to the acceleration of the submersible, and the direction is opposite to the acceleration direction. The inertial hydrodynamic force is related to the mass and velocity of the submersible. A common expression for the inertial hydrodynamic force of a submersible is as follows:

$$F = FD + FI \tag{4}$$

In this formula, F represents the hydrodynamic vector acting vertically on the unit length of the axis of the member, N/m; FD stands for resistance, and FI stands for inertial force.

2.2.5 Propeller propel

As the main power source of the submersible, the thruster is controllable. According to the arrangement of propellers on the submersible, the thrust generated by each thruster is decomposed, and the thrust vector on the three degrees of freedom is finally obtained as follows:

$$T = \begin{bmatrix} T_x & T_y & T_z \end{bmatrix} \tag{5}$$

To sum up, the submersible is mainly subjected to five forces: gravity G, buoyancy F_f, viscous hydrodynamic force f, inertial hydrodynamic force F, and thruster thrust T. The force diagram is shown in FIG. 2: The force diagram of the submersible.

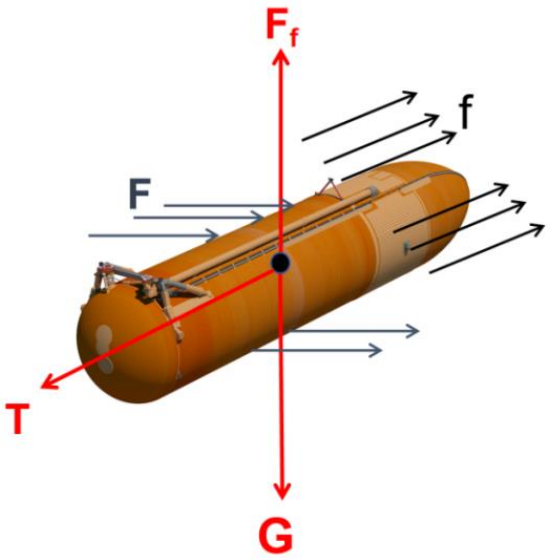


Figure 2. Schematic diagram of the force on the submersible

3. Dynamic Prediction and Environmental Response of Underwater Explorers

3.1. The establishment of the Kalman filter model

The state equation based on the Kalman filter is established for the diving process of the submersible:

$$X(t) = A \cdot X(t-1) + B \cdot U(t-1) + W(k) \tag{6}$$

Where, X(t) represents the state of the submersible at t, which is a vector of M×1, and M×M-dimensional matrix A represents the state transfer matrix, which represents the transfer relationship between the state of the system at t and the state of t + 1. The M × M matrix B represents the parameters of the dynamic system. U(t-1) is input by discrete system control, and W(k) represents system random noise.

In the x direction, the expression for the displacement and velocity of the submersible is as follows:

$$S_t = S_{t-1} + v_t \cdot \Delta t + \frac{1}{2} a_{t-1} \Delta t^2 \tag{7}$$

$$v_t = v_{t-1} + a_{t-1} \cdot \Delta t \tag{8}$$

Similarly, the expressions of displacement and velocity of the submersible in the y and z directions are the same as above.

At time t, the submersible's state is: $X_t = [S_t \quad V_t]^T$

3.1.1 When the submersible is in mechanical normal condition

When the submersible is in mechanical normal condition, the equation of state of the submersible is as follows:

$$X(t) = \begin{bmatrix} S_t \\ v_t \end{bmatrix} = \begin{bmatrix} 1 & \Delta_t \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} S_{t-1} \\ v_{t-1} \end{bmatrix} + \begin{bmatrix} \frac{1}{2}\Delta t^2 \\ \Delta t \end{bmatrix} \cdot a_{t-1} + W(k) \tag{9}$$

Where at-1 is U(t-1), which is controlled by the discrete system, and W(k) represents the random noise of the system.

3.1.2 When the submersible is in a state of mechanical loss

When the submersible is in a mechanical loss state, the equation of state for the submersible is as follows:

$$X(t) = \begin{bmatrix} S_t \\ \mathrm{v}_t \end{bmatrix} = \begin{bmatrix} 1 & \Delta_t \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} S_{t-1} \\ v_{t-1} \end{bmatrix} + W(k) \tag{10}$$

$$\mathrm{W(k)} = \begin{bmatrix} \Delta \mathrm{x} \\ \Delta \mathrm{v} \end{bmatrix} \tag{11}$$

At this time, the propulsion force of the submersible disappears, and W(k) has a great influence on the trajectory of the submersible, among which W(k) mainly includes three influencing factors: ocean current, ocean density, and seabed geographical location.

- Ocean current: The velocity is denoted as Δv_1, and the influence of ocean current on the movement of the submersible is considered in the x and y axes.
- Ocean density: $F_f = \rho g V$ Ocean density affects the buoyancy force on the submersible. The influence of ocean density on the movement of the submersible is considered in the z-axis direction.
- Geographical location of the sea floor: The Ionian Sea floor is relatively flat, with little

fluctuation and little elevation change, and can be regarded as approximately flat land. The topographic map of the Ionian seabed is shown in FIG.3:

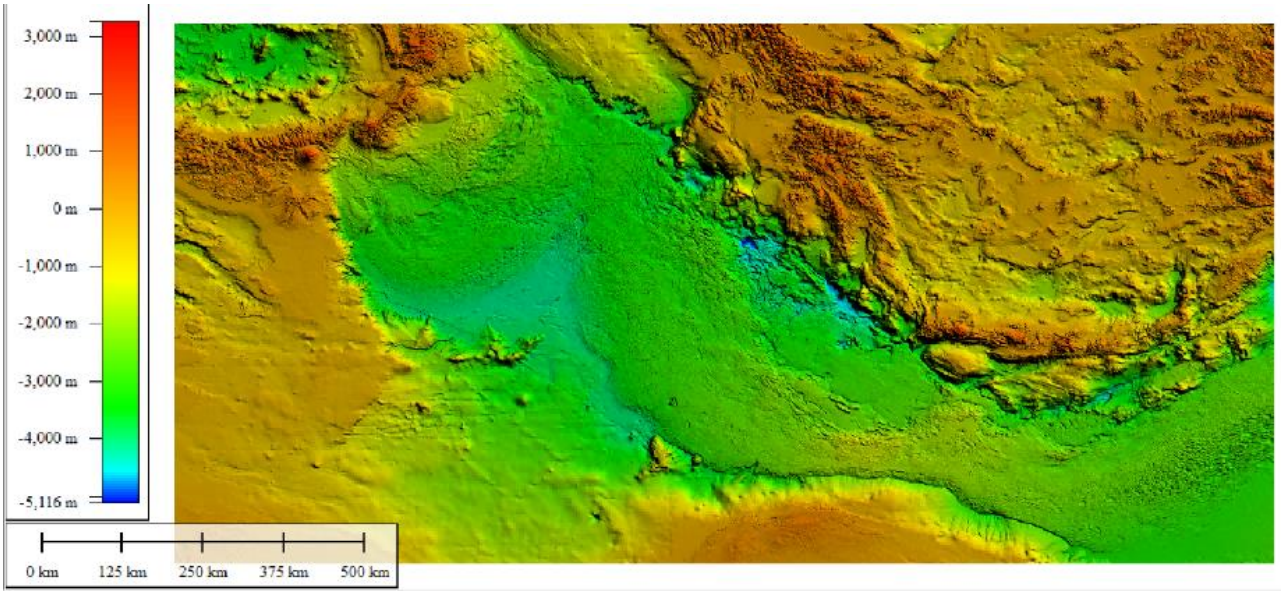


Figure 3. Topographic map of sthe Ionian seabed

- At the time of t-1, the submersible has a greater probability of the following two situations: the submersible is located at the bottom of the sea, and the submersible is at the neutral buoyancy point, so consider these two states.

➢ t-1 moment, when the submersible is on the ocean floor:

The value of the z coordinate is the depth of the seafloor, and the x and y values are affected by ocean currents.

The velocity expression of the submersible is: $\Delta v = \Delta v_1$

Assume that the acceleration expression of the submersible in this state is:

$$a_{t-1} = \frac{\Delta v}{\Delta t} \tag{12}$$

Then the displacement expression of the submersible is:

$$\Delta x = \Delta v \cdot t + \frac{1}{2} a_{t-1} \Delta t^2 = \frac{3}{2} \Delta v \cdot \Delta t \tag{13}$$

➢ t-1 moment, when the submersible is at the neutral buoyancy point:

Neutral buoyancy occurs when the average density of an object is equal to the density of the fluid immersed, resulting in buoyancy balanced by gravity, at which point the object neither sinks nor rises, at which point the value of the z coordinate no longer changes.

$$F_f = \rho g V = mg \tag{14}$$

In the x and y axes, the velocity expression of the submersible is:

$$\Delta v = v_1 \tag{15}$$

Assume that the acceleration expression of the submersible in this state is:

$$a_{t-1} = \frac{\Delta v}{\Delta t} \tag{16}$$

Then the displacement expression of the submersible is:

$$\Delta x = \Delta v \cdot t + \frac{1}{2} a_{t-1} \Delta t^2 = \frac{3}{2} \Delta v \cdot \Delta t \tag{17}$$

Note: The Kalman filter model is suitable for the situation where the submersible maintains communication with the main ship, the submersible sends signals to the main ship, and the main ship system receives observations to make predictions. It should be noted that the submersible may lose communication with the main ship. At this time, the main ship cannot receive the signal from the submersible, that is, the observation value is missing. The Kalman filter model is no longer used, but the motion trajectory value when the submersible maintains communication with the main ship can still be used to predict and deduce the motion trajectory when the submersible and the main ship disconnect communication.

3.2. Predictive model result

Based on the above model, the trajectory of the submersible was predicted for four scenarios, as shown in FIG. 4

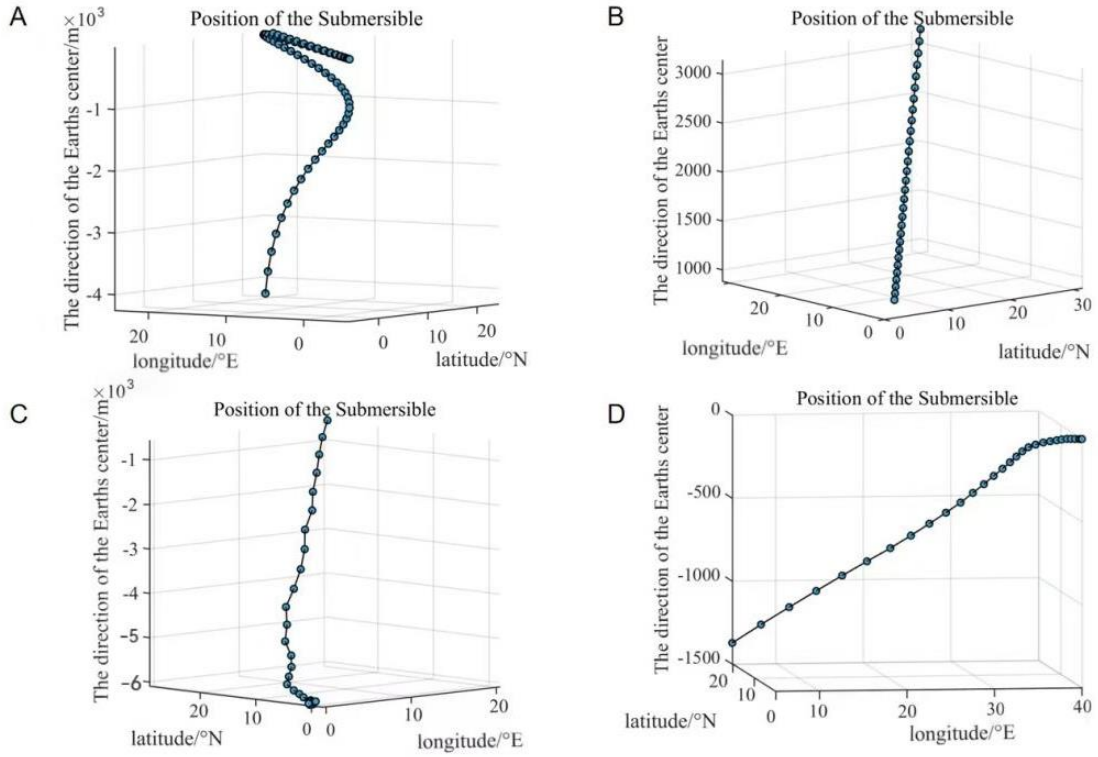


Figure 4. Submersible trajectory prediction simulation. A: When communications were lost and the submersible suffered mechanical defects. B: When there is a loss of communications and no loss of machinery. C: When there is no loss of communications and mechanical losses. D: When there is no loss of communications and no loss of machinery.

3.3. The uncertainty of forecasts

The prediction model has some uncertainty, mainly due to the following reasons:

Current effect: Ocean currents can affect the position of the submersible, causing it to deviate from its expected path.

Seawater density variance: The density of the water varies at different depths and geographical locations, which can also affect the position of the submersible.

Submarine topography: The topographic features of the seafloor, such as mountains, canyons, etc., will affect the path of the submersible, and thus affect its final position.

Mechanical failure: The submersible may experience mechanical problems, such as loss of propulsion, which may also cause the actual position of the submersible to deviate from its expected position.

Communication interruption: If the communication between the submersible and the main ship is interrupted, then the main ship will not be able to obtain real-time position information of the submersible, which will increase the uncertainty in predicting the location of the submersible.

To reduce the uncertainty in the above prediction, the submersible can regularly send some key information to the main ship before the accident, such as its current position, speed, direction, etc., as well as assemble some special devices, so that the main ship can predict the location of the submersible more accurately.

3.3.1 Equipment held by the submersible

First, the pressure shell is the core of the submersible pressure shell structure parts, The main deep water under pressure, needs enough strength and reliable sealing, providing protection for the internal equipment[8-9]. Second, propellers are the power source for the movement of the submersible and are responsible for pushing the submersible forward. Thirdly, observation and detection equipment which includes cameras, sonar, etc. can observe the surrounding environment and conduct seabed exploration. Fourth, deep sea searchlight can be used to illuminate the deep sea environment for easy observation and shooting. Fifth, underwater manipulators can be used for various underwater operations, such as collecting samples, repairing equipment, etc.[10]. Sixth, communication equipment will be used to communicate with the ground or other submersibles, transmitting data and commands. Seventh, power equipment can provide power to the various equipment of the submersible, usually including batteries and solar panels. Eighth, navigation equipment, including a compass, GPS positioning system, etc., can be used to determine the position of the submersible and navigation.

4. Conclusions

A Kalman filter-based state equation is established for the submersible diving process, whether the submersible maintains communication with the host ship or not, and whether there are mechanical defects are discussed in separate scenarios, and the prediction model of the submersible's position is shown in 3.2. Cow rate currents, ocean density, seafloor geographic location, and the position of the submersible on the prediction of the uncertainty in the prediction are the effect of ocean currents, the difference in seawater density, and the seafloor topography. To reduce the uncertainty in the prediction mentioned above, the submersible needs to send some key information to the main vessel: speed and direction, mechanical status, environmental data, and communication status. The equipment required for the submersible is observation and detection equipment, communication equipment, power supply equipment, etc.

This study reveals the feasibility of Method Kalman filtering which can provide a research idea and framework for the field of ocean engineering and technology.

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