Advances in Computer Science Research, volume 87
3rd International Conference on Mechatronics Engineering and Information Technology (ICMEIT 2019)

Research on Thermocline Tracking based on Multi-AUVs Formation

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Abstract. Thermocline is of great significance to marine scientific research. Multi-autonomous underwater vehicles (AUVs) have great advantages over single autonomous underwater vehicle in ocean observation. In order to solve the multi-AUVs for Thermocline tracking problem, firstly, an AUV thermocline tracking method is proposed based on Kalman filter estimation algorithm. Then, an AUV motion controller based on state feedback is designed by using $H\infty$ robust control method. Finally, a thermocline tracking method with vertical distribution of multi-AUVs formation is proposed and implemented in simulation environment.

Keywords: multi-AUVs (Multiple Autonomous Underwater Vehicles), thermocline tracking, AUV's motion control, $H\infty$ robust control.

1. Introduction

Ocean thermocline is very important for ocean research, and AUV (autonomous underwater vehicle) is an ideal choice for thermocline tracking. At present, tracking the ocean thermocline is mainly to determine the upper and lower boundaries of the thermocline, and then let the underwater vehicle do "yo-yo" movement in this range. The methods to determine the upper and lower bounds of thermocline mainly include vertical gradient method, peak method and optimal segmentation method [1-4]. In 2009, MIT carried out a thermocline tracking experiment by using a single underwater vehicle. During the experiment, the average temperature gradient is regarded as the critical value of thermocline tracking, and the depth greater than the average temperature gradient is regarded as the thermocline, so as to determine the upper and lower bounds of the thermocline and make the AUV "yo-yo" in this range [5]. In 2010, Zhang Yanwu and others carried out thermocline tracking experiments using Tethys AUV in Monterey Bay. During the experiment, by determining the location of the extreme temperature gradient and extending a certain distance from the top to the bottom of the thermocline artificially, as the upper and lower boundaries of the thermocline, AUV moves "yo-yo" between the upper and lower boundaries of the thermocline every time [6]. In China, Wu Wei et al. [7] compared and discussed several methods for determining thermocline boundary based on the measured CTD data in the South China Sea in detail, and discussed the key considerations under different conditions of deep and shallow water.

Compared with single AUV, multi-AUVs formation has incomparable advantages in ocean thermocline tracking, such as: multi-AUVs formation can cover more areas; each AUV in multi-AUVs formation has smaller volume, simpler control system and stronger fault tolerance.

In this paper, a new method for determining the upper and lower boundaries of thermocline is proposed based on Kalman filter estimation method. Then, the H_∞ robust control is used to realize the AUV motion control based on state feedback. Finally, a method for tracking the thermocline with multi-AUVs formation vertical distribution is proposed.

2. Thermocline Tracking Method

The vertical gradient method is commonly used in the calculation of thermocline characteristic [8]. Because of the subjectivity of the peak method and the large amount of computation of the optimal segmentation method, a thermocline tracking method based on the vertical gradient method is proposed in this paper.

According to the lowest standard of thermocline strength stipulated in reference [9, 10], the threshold of temperature gradient is 0.05 in deep water (where the water depth is greater than 200 m) and 0.2 in shallow water (where the water depth is less than 200 m).

In the process of tracking thermocline, the temperature data obtained by AUV are used to calculate the "upper three temperate gradients", "current temperature gradients" and "the next temperature gradient". The formula for calculating the temperature gradient is as follows:

$$T\_grad = (T - T\_pre) / (depth - depth\_pre) \tag{1}$$

In equation (1), T_grad is the calculated temperature gradient. T is the temperature of current depth. T_pre is the temperature of the previous depth. $depth - depth\_pre$ is the change of depth.

And the meanings of "the previous temperature gradient value", "the current temperature gradient value" and "the next temperature gradient value" are as shown in figure 1.

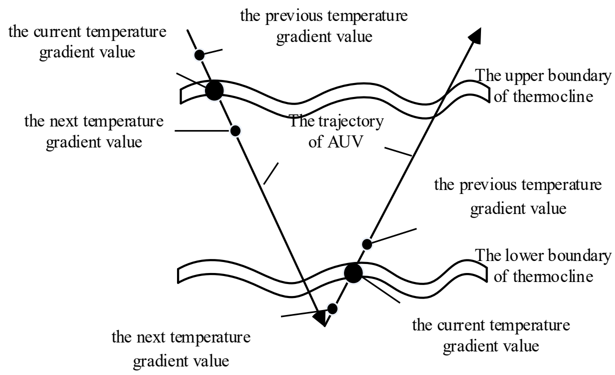

Fig. 1 The relationship between temperature gradient and depth

According to Kalman filtering principle, the state equation and observation equation of the temperature measurement system can be set as follows:

$$\begin{aligned} x_k &= x_{k-1} + w_k \\ y_k &= x_k + v_k \end{aligned} \tag{2}$$

In equation (2), w_k and v_k is process noise and measurement noise respectively. And there the variance is $Q_k = 0.01, R_k = 0.05$. The temperature x_k at the k time is predicted according to the x_{k-1}. And y_k is measured by the temperature sensor.

According to the above temperature measurement system, Kalman filter recursive equation is used to estimate the "next temperature value". And using the equation (1) to get "the next temperature gradient".

After obtaining the temperature gradient, we determine the relationship between the temperature gradient and the threshold (-0.2 $^oC/m$), and identify the upper and lower boundaries of thermocline.

1. If "the current temperature gradient value" (negative) is not more than the threshold and "the first three temperature gradient values" are more than the threshold and "the next temperature gradient value" is less than the threshold, we think that this is the upper boundary of thermocline.

2. If "the current temperature gradient value" (negative) is not more than the threshold and "the first three temperature gradient values" are less than the threshold and "the next temperature gradient value" is more than the threshold, we think that this is the lower boundary of thermocline.

Because the temperature data acquired by AUV contains noise, the calculated temperature gradient needs to be de-noised. Generally speaking, one dimensional data denoising can be achieved by sliding window average filtering and five-point three-time filtering. Sliding window average filtering regards N sampled values obtained continuously as a queue. The length of the queue is fixed to N. A new data is sampled at the end of the queue, and the original data of the head of the queue is discarded (following the first-in-first-out principle). The arithmetic data of the N data in the queue are calculated and the new filtering results are obtained. The principle of the five-point cubic filtering algorithm is that if the observed data at n isometric points are known, two adjacent points can be selected before and after each data point, and approximated by the cubic polynomial shown in equation (3).

$$Y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 \tag{3}$$

In equation (3), a_0, a_1, a_2, a_3 is determined by least square method.

Using the above two filtering methods, the temperature gradient data obtained from a sea trial are filtered and processed, which is shown in Figure 2.

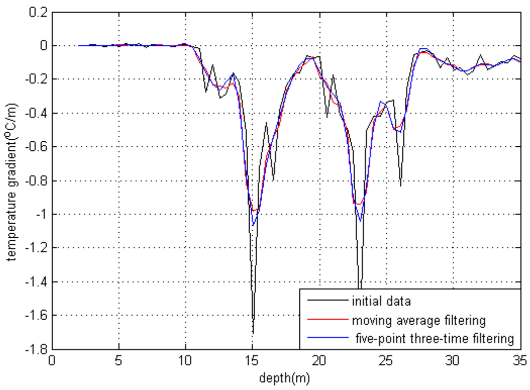

Fig. 2 The results of temperature gradients filtering

In Figure 2, the black line represents the temperature gradient calculated from the original temperature data, the red line represents the sliding average filtering result, and the blue line represents the five-point cubic filtering result. As can be seen from the above figure, the temperature gradient obtained by moving average filtering is smoother, while the result obtained by five-point cubic filtering is closer to the original data, and the effect of noise removal is obvious. Therefore, this paper will use five-point cubic filtering to smooth the temperature gradient data in the follow-up simulation and verification process.

3. Design of AUV Vertical Motion Controller

Because the AUV system can be described by unknown bounded uncertainty model within a certain range [11], and robust control can effectively overcome the uncertainties and disturbances of AUV's systems. Therefore, this paper will use the robust control method to study the motion control system of small AUV. Combined with AUV vertical surface motion model [12]:

$$\begin{aligned} m(\dot{w} - uq) &= Z_{\dot{q}}\dot{q} + Z_{\dot{w}}\dot{w} + Z_{uq}uq + Z_{uw}uw + (P - B_0)\cos\theta + u^2 Z_{uu}\delta_s \\ I_{yy}\dot{q} &= M_{\dot{q}}\dot{q} + M_{\dot{w}}\dot{w} + M_{uq}uq + M_{uw}uw + u^2 M_{uu}\delta_s \end{aligned} \tag{4}$$

Because the current depth D, vertical velocity w, pitch angle θ and angular velocity q of AUV satisfy the following relationships:

$$\dot{D} = w\cos\theta - u\sin\theta,\ \dot{\theta} = q \tag{5}$$

Because during the thermocline tracking process $\theta \approx 0$, there is $\sin\theta \approx \theta, \cos\theta \approx 1$. And the state of system is $x = [w, q, \mathrm{D}, \theta]^T$. So, according to equation (4) and equation (5), we can get the state space model of the system.

$$M\dot{x} = A_s x + B_s \delta + d_1 \tag{6}$$

And,

$$M = \begin{bmatrix} m - Z_{\dot{w}} & -Z_{\dot{q}} & 0 & 0 \\ -M_{\dot{w}} & \mathrm{I}_{yy} - M_{\dot{q}} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},\ A_s = \begin{bmatrix} Z_{uw}u & Z_{uq}u + mu & 0 & 0 \\ M_{uw}u & M_{uq}u & 0 & 0 \\ 1 & 0 & 0 & -u \\ 0 & 1 & 0 & 0 \end{bmatrix}\quad B_s = \left[u^2 Z_{uu},\ u^2 M_{uu},\ 0,\ 0\right]^T, d_1 = \left[P - B_0, 0, 0, 0\right]^T$$

It is written in a standard form:

$$\begin{aligned} \dot{x} &= Ax + Bu + w \\ y &= Cx \end{aligned} \tag{7}$$

and, $A = M^{-1}A_s, B = M^{-1}B_s, u = \delta, w = M^{-1}d_1, \mathrm{C} = [0\ \ 0\ \ 1\ \ 0]$.

The tracking error of the system is: $e(t) = y - D_{com} = Cx - D_{com}$. In order to achieve a good tracking effect for AUV in thermocline tracking process, the integral term of tracking error should be added to the controller, namely:

$$x_s(t) = \int_0^t e(\tau)d\tau = \int_0^t \left[Cx(\tau) - D_{com}\right]d\tau \tag{8}$$

When initial condition is $x_s(0) = 0$, there is $x_s(t) = Cx(t) - D_{com}$.

Thus, an augmented description of the system (7) can be obtained and define $x_a = \left[x^T\ \ x_s^T\right]^T$.

$$\begin{aligned} \dot{x}_a &= \begin{bmatrix} A & 0 \\ C & 0 \end{bmatrix} x_a + \begin{bmatrix} B \\ 0 \end{bmatrix} \delta_s + \begin{bmatrix} w \\ -D_{com} \end{bmatrix} \\ y &= \begin{bmatrix} C & 0 \end{bmatrix} x_a \end{aligned} \tag{9}$$

The state feedback controller for the above system is designed as follows:

$$\delta_s = \begin{bmatrix} K_1 & K_2 \end{bmatrix} \begin{bmatrix} x \\ x_s \end{bmatrix} = K_1 x + K_2 x_s = K x_a \tag{10}$$

Thus, the closed loop system of AUV vertical plane can be described as:

$$\begin{aligned} \dot{x}_a &= \begin{bmatrix} A + BK_1 & BK_2 \\ C & 0 \end{bmatrix} \begin{bmatrix} x \\ x_s \end{bmatrix} + \begin{bmatrix} w \\ -D_{com} \end{bmatrix} = \left[A_a + B_a K\right] x_a + w_a \\ y &= \begin{bmatrix} C & 0 \end{bmatrix} x_a \end{aligned}$$

For the above system, it can be converted to linear matrix inequality (LMI) problem.

4. Multi-AUVs Formation Thermocline Tracking Method

In order to track the thermocline in the vertical distribution of multi-AUVS formation, the formation method shown in Figure 3 is designed in this paper. Each AUV is vertically distributed and spaced at a certain distance.

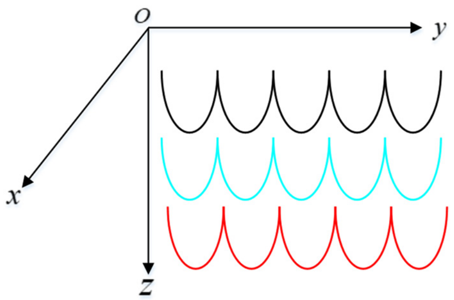

Fig. 3 Multi-AUVs formation distribution mode

When we use multi AUV formation to track thermocline, we first need to determine the upper and lower boundary of thermocline, and then track thermocline according to the algorithm for thermocline tracking.

The AUV motion controller designed in the third section is used to control the motion of AUV. The horizontal velocity of each AUV is set to 2 m/s, and the depth control input is a sinusoidal signal to simulate the "yo-yo" motion. In the process of thermocline detection, each AUV uses the thermocline tracking method proposed in second section to determine whether it is in the thermocline to determine the location of the thermocline. Finally, the detection results of each AUV are integrated to determine the upper and lower boundary positions of thermocline.

The validity of the thermocline tracking method proposed in this paper is verified by using the temperature data obtained from an AUV sea trial. In the simulation, the motion control of AUV is realized by the control method in the third section, and the parameters of AUV model in reference [12] at 4.3 chapter are used.

Through simulation, we get the simulation results shown in Figure 4. For the sake of visualization, the results of the vertical section are displayed.

In Figure 4, the blue solid line is the trajectory of multi-AUVs formation, the red dot is the boundary position of thermocline detected by AUV, and the green solid line is the actual boundary position of thermocline. It can be seen from the figure that the position of thermocline boundary can be found more accurately by AUV formation. Finally, the upper and lower boundaries of thermocline can be found by combining the detection results of each AUV. It can also be seen from the figure that this formation method can cover a larger vertical section area than a single AUV, can better decompose tasks, reduce the task load of a single AUV, and give full play to the advantages of multi-AUVs formation.

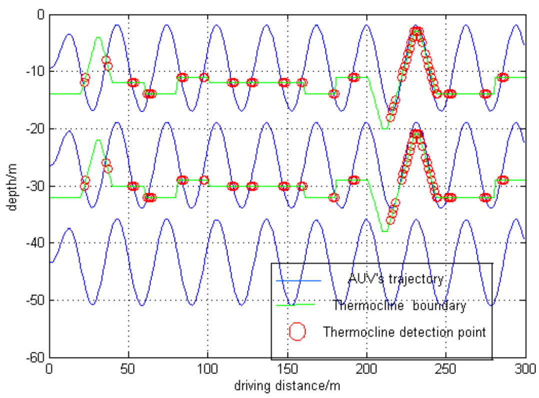

Fig.4 The results of multi-AUVs formation thermocline tracking

5. Summary

Firstly, based on Kalman filter, a thermocline tracking algorithm is proposed, which enables AUV to obtain the temperature gradient of the next time in advance in the thermocline tracking process, and has predictability. Secondly, due to the great changes in the ocean environment during the thermocline tracking process, it is necessary for the AUV controller to have a certain anti-jamming ability. In this paper, a horizontal and vertical motion controller of AUV is designed based on robust H method. Finally, a thermocline tracking method for multi-AUV formation with vertical distribution is proposed, and the simulation results are validated by using the parameters of an AUV model and the temperature data obtained from sea trials. The simulation results show that the proposed multi-AUVs formation thermocline tracking method can identify the upper and lower boundaries of the thermocline and track the Ocean thermocline.

Acknowledgements

This work is supported by the National key research and development program (2017YFC0305901), National Natural Science Foundation of China (91648204, 41376110), Innovation fund of the Chinese Academy of Sciences (CNJJ-16M1225), the Doctoral Scientific Research Foundation of Liaoning Province (201501035). And the author would like to thank the SIA team, Xinyu Liu, Shuxue Yan, Lian Wu and other relative persons.

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