Underwater Pipeline Detection and Following of AUV Based on the Optic Vision

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***Abstract*—It is becoming more and more common to use Autonomous Underwater Vehicles to perform tasks underwater, such as the inspection of underwater structures. Following some previous work, this paper describes a new AUV framework based on the optic vision for underwater pipeline detection and following. The controller of AUV is designed by combining the fuzzy control method with PID control structure, and two improved approaches are selected to adjust the motion state constantly. Hough transforming is used to extract the straight line of pipeline boundary, and some strategies are brought forward to reduce computation burden and improve the accuracy of extraction. The proposed method has been tested by a certain AUV, the results show that the proposed method is feasible.**

Keywords—AUV; pipeline detection; Hough transforming; reference zone;

I. INTRODUCTION (*Heading 1*)

Submarine pipeline is the lifeline of offshore oil and gas field, and the purpose of inspection is mainly to reveal the actual defects and problems of submarine pipeline. The results obtained can be used to evaluate the status of pipeline, and precautionary measures can be take, so it is particularly important for the offshore oil development to survey the status of submarine pipeline[1]. At present, the condition of pipeline in the neritic zone is mainly checked by the divers, and in the depth of hundreds of meters is done by the remote operation vehicle(ROV).For the existence of surface mother ship, the operation cost of ROV is high, and its operating range is also limited for the length of umbilical cables. If the cable is wound or broken open by something in the complicated underwater environment, the loss accident of ROV is often caused. So it is the most economical and higher efficiency way to inspect submarine pipeline by autonomous underwater vehicle (AUV) at present[2].It is also a hot issue on how to use AUV effectively to survey the pipeline.

On basis of some previous work, the problem that AUV detected and tracked the pipeline automatically were studied further, and a new AUV framework based on the optic vision for underwater pipeline detection and following was proposed. Firstly, the hardware architecture and software architecture of AUV system were introduced detailly. Secondly, the controller of AUV is designed by combining the fuzzy control method with PID control structure, and two local adjustment strategies are selected to improve the stability of position control and velocity control. Then, the image process method was discussed. Finally, its effectiveness is verified by the tank test, and the results can provide some reference for the specific application of AUV.

II. "ZT" AUV DEPICTION

"ZT" AUV is designed as an integrated ocean exploration AUV. The prime missions are to survey submarine terrain, detect and identify underwater objects, detect ocean oil-gas pipelines, acquire ocean environment data. "ZT" AUV has a shape of prolate globularity(shown as Fig.1), and the detail parameters is shown in Tab.1. It can be divided into 8 subsystems according to the system function and mission requirement, such as control system, underwater navigation system, communication system, system of object detecting and environment data acquisition, execution system, safety checking system, self-rescue system and power system.

Fig. 1. "ZT" AUV

TABLE I. SPECIFICATION OF "ZT-AUV" ITEM VALUE REMARK

Weight	5200 kg in the air
Length	6.8 m
Width	1.9 m including the elevating rudder
Height	1.19 m
Regular Speed	4-5 kn
Maximal Speed	7 kn
Speed During Detecting	1-2 kn
Current Resistibility	3-4 kn
Maximal Voyage Distance	500 km
Maximal Working Depth	500 m

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III. CONTROLLER DESIGN OF AUV

The controller of AUV is designed by combining the fuzzy control method with PID control structure, and it is described as

$$f = \frac{2}{1+\exp(k_1 e + k_2 \dot{e})} - 1 + \Delta f \tag{1}$$

Where k_1 and k_2 are Control parameters, and they are the same as the parameters in the PD control method. e and $\dot{e}$ are control input, which represent the deviation and the deviation change rate respectively.

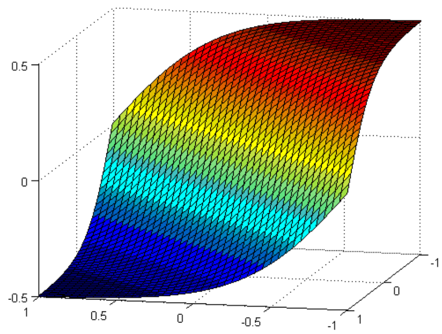


Fig. 2. Curve of S surface

When AUV detects and follows the underwater pipeline, it have to adjust the motion state constantly, so two improved approaches are selected. Firstly, considering the stability of position control, the local adjustment strategy is selected to avoid the shocks caused by hysteresis, and Δf is defined as

$$\Delta f = S(\Delta e), \tag{2}$$

where $S(x) = \dfrac{1}{1+e^x} - 1$, and $\Delta e = \gamma[(1-\delta)e + \delta\alpha\beta\int edt]$. The values of γ, α, β and δ are determined according to the values of $|\dot{e}|$ and $\dot{e}\cdot e$. Secondly, considering the stability of velocity control, the formula (1) is written as

$$f = \sum k[\frac{2}{1+\exp(-k_1 e - k_2 \dot{e})} - 1], \tag{3}$$

where k is expressed as $k = k_\varepsilon + k_a$, and k_ε is constant, and $k_\varepsilon = C_1 sign(e\cdot\dot{e}) + C_2|e| + C_3|\dot{e}|$, so the overshoot is reduced, and the convergence speed is improved.

On this basis, decision mechanisms of AUV based on behaviour is used. It includes five basic behaviours in five different kinds of condition, such as the movement in the fixed depth, the movement of tracking pipeline. First, AUV is controlled to move in the fixed depth. When it reaches the specified depth, it begin to search the pipeline based on the optic vision. Once the pipeline is detected, the position information of pipeline is calculated for the navigation of AUV. If the pipeline is lost, it may be buried or goes along another direction, so AUV will move in a low speed or it enter the search state.

IV. FRAMEWORK OF OPTIC VISION SYSTEM

Optic vision system consists of optic vision computer, underwater CCD camera, tripod head and auxiliary underlight(Fig.3). The computer with a graphic card based on PC104 bus is the core part of system. It is used for the image acquisition and image data processing. Through the network, the location information of pipeline is transmitted to the computer of path planning system, and the movement and attitude information of AUV are obtained from the computer of control system punctually, which are used for the predication of reference region. Thus, the visual modelling, high-level visual information processing and understanding, and information exchange with the other computer systems are completed. Underwater camera is equipped with auxiliary underlight. Along with the change of natural illumination and image grey, light control device can adjust the light intensity automatically. The position and angle of camera and light can be adjusted through the head. The control commands of camera, head and light are operated by the serial card on the on-board computer.

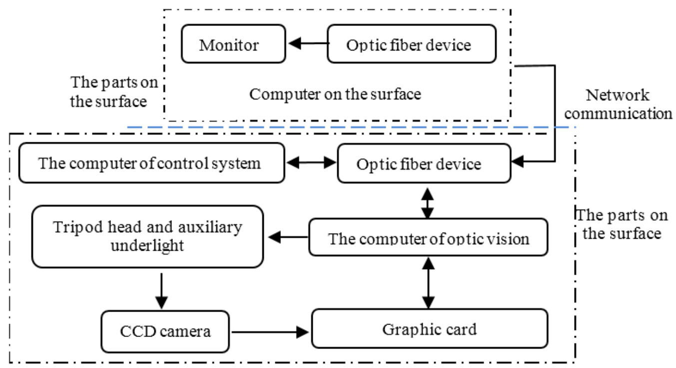


Fig. 3. The hardware structure of vision system

Based on the visual theory of Marr, the software architecture of underwater optical vision system includes two parts (Fig.4): the middle layer and the high-level layer. The middle layer is for the image processing, such as image preprocessing, edge detection, feature extraction. The initial understanding and evaluation on pipe image are output. High-level layer is the ultimate implementation part of underwater pipeline tracking system.The line features are extracted, and the parameters of pipeline are identificated by them. Combined with attitude information of AUV, navigation information of pipeline location is determined, and the possible region is predicted by the Kalman filter, where pipeline may be appear in the next time.

A. Image pre-processing

Image pre-processing includes several parts,such as image filtering, image segmentation, morphological processing and edge detection ect.The purpose is mainly to obtain the outline of underwater pipeline in the image, so the methods selected are more focused on the results of practical application. They are as following:

(1) Image filter

Filtering for noise smoothing is an absolute necessity in the case of images as noise is common, especially in the case of underwater pipeline images. The filtering part is also generally very time consuming, Several filtering techniques (mean, median, Gaussian) have been tried, and it is found that a good compromise between quality and speed is reached using the median filter. So a median filter (7×7) is selected to remove the environment noise in the paper.

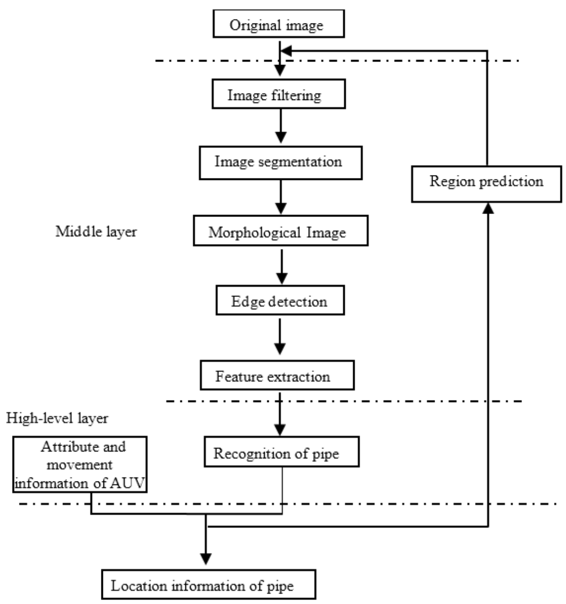


Fig. 4. The software structure of vision system

(2) Image segmentation

A single, fixed threshold, generally gives results which are highly dependent on the background level. AUV surveys the pipelines at the status of movement, which are often on different condition of illumination, so it can't satisfy the demand of inspection. The method based on iterative optimal threshold is chosen. The idea is to estimate the value of threshold in accordance with the background information [3], and to separate the pipeline from the image background. The iterative procedure is described as:

①To select an initial estimate value as the threshold T;

②To use T to segment the image. It will produce two groups of pixels: R_1, in which intensity values of pixels are greater than T; R_2, in which intensity values of pixels are less than T.

③To compute the average intensity value μ_1 and μ_2 for the pixels in regions R_1 and R_2;

④To compute a new threshold value T: $T=(\mu_1+\mu_2)/2$

⑤ To repeat ② through ④ until the difference in T in successive iterations is smaller than a predefined parameter T_0.

(3) Morphology processing

For the uneven distribution of image gray and obscure information of pipeline edges, a large number of isolated points, thin protrusions and small holes are often existed in the binary underwater images, so two morphological operations (opening and closing) are selected to eliminate or fill these regions, so that the quality of images can be improved and they are more suitable for subsequent information extraction.

(4) Edge detection

Purpose of edge detection is to extract the outer contours of pipeline in the images so as to analyze the shape feature of pipeline. Sobel edge detector is selected in the paper. The basic idea is to use a smooth surface to fit the gray value of pixels, which are in the neighborhood of the computed point, and then to calculate the first or second derivative of surface. The method is not simple but also has better real-time.

B. Edge extraction based on the improved Hough transform

After edges are detected, Hough transform can be used to extract the straight line features information of pipeline boundary[4]. In order to reduce the amount of computation and improve the accuracy of extraction, two aspects of improvement are brought forward, which is combined with the results of image pre-processing before-mentioned.

(1)Remove false edge points

A moving window is used to search the effective area, and to estimate the region area, which is constituted by the edge pixels detected in the window. The value of region saturation is computed, which is defined as the value of region area by window area. By comparing the value of region saturation, the edge information is determined whether it is right or not. The specific procedure is described as:

①To set the step of the search window, which is depended by the dimension of actual image.

②To determine the region area composed by edge pixels. Some pixels at the edge of regions are obtained by line scanning. So the area of each region can be determined by the appropriate geometric relationship.

③To computer the region saturation, which is determined by the size of region area and the window area.

④ To remove pseudo- edge pixels. Compared with the threshold value, if the value of region saturation is greater, the region is consisted by the pseudo-edge pixels, and they should be removed.

(2) Clear the value around the peak point region

In Fig.5, L is set as the detected line, and the point $E(\rho_{max}, \theta_{max})$ is denoted as the peak point. The distance between line L and line L_1 or line L_2 is denoted as $\Delta\rho$. For the peak point $E(\rho_{max}, \theta_{max})$, the cumulated value in its region (ρ_i, θ_i) is $S(\rho_i, \theta_i)$,then the following formula is often selected:

If: $\rho_{max}-\Delta\rho \le \rho_i \le \rho_{max}+\Delta\rho$ and $\theta_{max}-\Delta\theta \le \theta_i \le \theta_{max}+\Delta\theta$, then:

$$S(\rho_i, \theta_i) = 0 \quad (3)$$

The region described by the formula (3) is denoted as R_{abcd}, which is determined by four points A,B,C,D[5]. Although random point in region can't generate a straight line, but some lines made by other regions (such as L3) may still be detected[6]. For this reason, a method is taken to clear the value. In the image space, if region R_{abcd} near the line L is found, pixels in this region are searched in the parameter space at interval of angle, and the values corresponded in the accumulator are cleared, so these points can't generate lines in this region. Thus, it is ensured that there is only one line detected as the boundary line in the region. So position information of pipeline is more accurate.

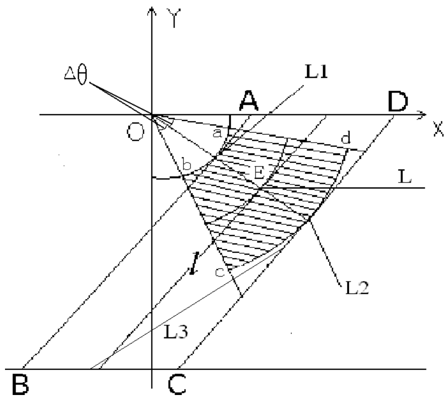
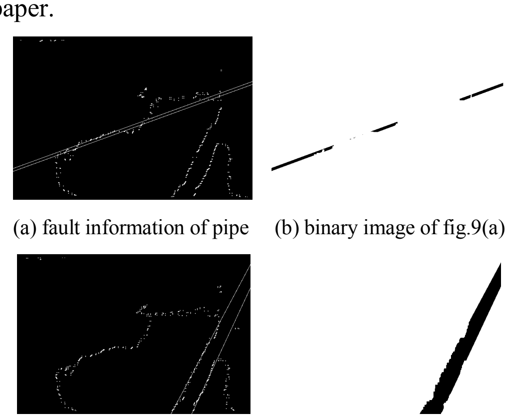


Fig. 5. Line condition after process

C. Results verifing

According to the characteristics of the underwater pipeline images (Fig.6), if line isn't the boundary of pipeline, the binary regions are formed as non-connected regions [7], which are composed by several independent regions. If it is the boundary, the region should be connected. So the connectivity relationship among the regions is selected to judge the results in the paper.



(a) fault information of pipe (b) binary image of fig.9(a)

(c)information of pipe (d)binary image of fig.9(c)

Fig. 6. The judgment of pipeline information

D. Region prediction

The speed of AUV is not fast, so the attitude has little affection for the pipeline in the image, and the change of region is also small among frames. For these reasons, a reference region of pipeline can be predicted by Kalman filter.

The prediction algorithm of Kalman is as follows[8]

①to calculate the gain

$$K_t = P_t^- H^T (HP_t^- H^T + R)^{-1} \tag{4}$$

②to update state equation according to the measurement

$$\hat{X}_t = \hat{X}_t^- + K_t(Z_t - H\hat{X}_t^-) \tag{5}$$

③to Update the error covariance matrix

$$P_t = (I - K_t H)P_t^- \tag{6}$$

④to obtain the estimated value

$$\hat{X}_{t+1}^- = \Phi \hat{X}_t \tag{7}$$

⑤to estimate the covariance matrix

$$P_{t+1}^- = \Phi P_t \Phi^T + Q \tag{8}$$

If (ρ_{c1}, θ_{c1})、(ρ_{c2}, θ_{c2})、(ρ_M, θ_M) are denoted as the math description of two borders and the central axis of pipe, the state vector of the boundary region can be expressed as $X_t = (\rho_M, \theta_M, \rho_{c1}, \theta_{c1}, \rho_{c2}, \theta_{c2})$ in t time, then the system state model can be expressed as $X_{t+1} = \Phi X_t + W_t$,where W_t denotes as the system noise, and the state transition matrix is defined as $\Phi = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$.

Observed value $Z_t = (\hat{\rho}_M, \hat{\theta}_M)$. It is denoted as the math description of the pipeline in t time, so the system measurement model is denoted as $Z_t = HX_t + V_t$, where V_t is the measurement noise, and $H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$.

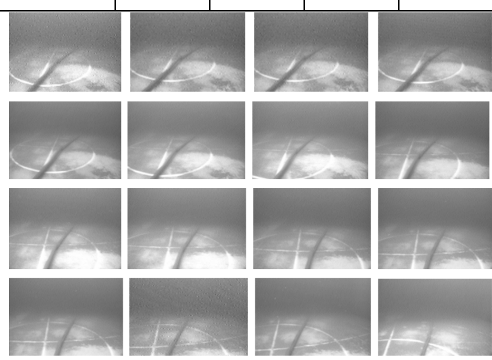
Based on the above state model, measurement model and other initial conditions, Kalman filter can be used to estimate the state vector $\hat{X}_{t+1}^-$ and covariance matrix P_{t+1}^- of pipeline region in the next frame.

V. RESULTS

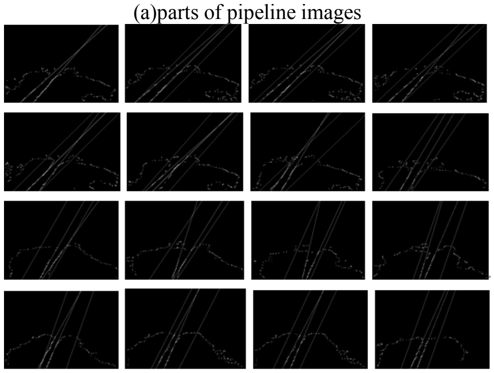
In order to evaluate the system proposed in the paper, a series of tests are carried out in the tank of the laboratory of autonomous underwater vehicle in Harbin University in China. The specific parameters of tank are 50m × 30m × 10m.The pipelines are simulated by 5 sewer pipes, which are 6 meters long and its diameter is 250mm. They are placed from east to west underwater, "ZT" AUV finishes the detection and tracking of pipes automatically. The results are shown in Tab.II and Fig.7-Fig.8. From test results in tank, the processing speed of system is within 0.5s per frame and the correct rate is more than 90%. It shows that the control method and data process method are competent for pipeline tracking. They can provide some references for AUV to detect underwater pipeline based on optic vision in practical application.

TABLE II. THE EXPERIMENT RESULT OF PIPELINE TRACKING

times	1	2	3	4	5
sampled data (frame)	400	428	450	475	500
Processing time （s /frame）	0.34	0.39	0.41	0.45	0.38
Correct results (frame)	382	397	423	446	476
Fault results (frame)	5	6	8	8	7
No information (frame)	13	25	19	21	17
Correct rate	95.5%	92.7%	94.0%	93.4%	95.2%



(a)parts of pipeline images



(b)results by processed

Fig. 7. The pipeline and corresponding processing results during experiment

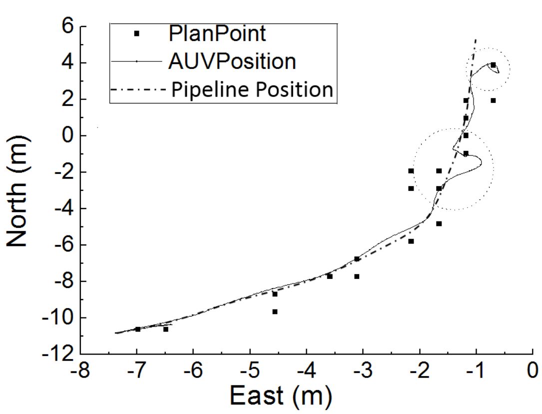


Fig. 8. Results of Underwater Pipeline Detection and Following of AUV

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