Proceedings of 2017 IEEE
International Conference on Mechatronics and Automation
August 6 - 9, Takamatsu, Japan

An Underwater Pipeline Tracking System for Amphibious Spherical Robots

Liwei Shi[1,2*], Zhan Chen[1,2], Shuxiang Guo[1,2,3], Ping Guo[1,2], Yanlin He[1,2], Shaowu Pan[1,2], Huiming Xing[1,2], Shuxiang Su[1,2], Kun Tang[1,2]

[1] Key Laboratory of Convergence Medical Engineering System and Healthcare Technology, the Ministry of Industry and Information Technology, Beijing Institute of Technology, No.5, Zhongguancun South Street, Haidian District, Beijing 100081

[2] Key Laboratory of Biomimetic Robots and Systems, Ministry of Education, Beijing Institute of Technology, No.5, Zhongguancun South Street, Haidian District, 100081 Beijing, China.

[3] Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa 760-8521, Japan

Email: shiliwei@bit.edu.cn, chenzhan@bit.edu.cn, guoshuxiang@bit.edu.cn

* Corresponding author

***Abstract* - Based on monocular camera, an underwater detection and tracking system for amphibious spherical robot is proposed to realize autonomous cruise of underwater pipelines. Firstly, according to the imaging characteristics of underwater image, the image of pipeline is detected by image binarization, edge detection and Hough transform. And then, the Kalman filter was carried out according to the edge information and the underwater pipeline was tracked. The control scheme of the visual system to the amphibious spherical robot was improved, and the tracking pipe motion of the amphibious robot is controlled by PID algorithm. Finally, we carried out some experiments under different scenes to demonstrate the effectiveness of the proposed underwater pipeline tracking system, and the experimental results showed that the proposed underwater pipeline tracking algorithm has good robustness and real - time performance.**

Index Terms - Amphibious Spherical Robot; Pipeline Inspection; Kalman Filter; PID Control; Pipeline Tracking

I. INTRODUCTION

Underwater pipeline is an important part of offshore oil and gas field development system. In the deep sea, oil pipelines are often exposed to the seabed [1], which needs to be checked regularly, but the marine environment is complex and the safety of the driver is not well protected. Underwater robots can perform many tasks in place of divers, with features such as high security, good economy, and strong functionality. In the process of underwater submarine pipeline inspection, the most critical is to achieve the automatic tracking of underwater pipelines.

The detection of underwater targets has been a hotspot in research in recent years. An algorithm that uses color characteristics had been proposed by S. Bazeille [2] to detect targets. The paper [3] realized the underwater image target detection algorithm based on the PSO and the fuzzy partition entropy. Dynamic window detection method was adopted to improve the accuracy and real-time performance of the underwater robot pipeline detection system in the paper of X. Tang [4]. An on-line system using computer vision algorithms had been presented by Paulo Drews Jr to detect an underwater cable-like target [5]. A nonlinear image-based visual servo control algorithm was described for the pipeline tracking problem by S. Krupinski [6]. C. Berger presented a vision-based guidance and control system for the path tracking of autonomous underwater vehicles [7]. The linear fast detection method based on contour information is applied to the submarine pipeline detection robot [8]. Gaussian filtering and image segmentation techniques are used to extract digital images and realize the computer interpretation of the pipeline image [9].

In this paper, an underwater pipeline tracking system for amphibious spherical robots is designed based on vision. According to the characteristics of underwater image, the gray-scale image is processed first, the histogram equalization is made using Gaussian filter to reduce noise, and threshold segmentation algorithm is used to binarize the image. Then, the canny operator is used to detect the edge of the pipeline in the image and the application of the Hough transform to the edge of the pipeline are simulated. Finally, in the subsequent video frame, Kalman filter is used to track and feedback the control quantity, and the motion of the spherical robot is realized based on the improved control scheme.

The main structure of this article is as follows, the composition of the amphibious spherical robot and the tracking system is introduced in section 2, section 3 provides the detection of underwater pipeline image, section 4 introduces the underwater pipeline tracking, section 5 shows some experimental results, and finally some conclusions are provided in section 6.

II. SYSTEM COMPOSITION

A. *Amphibious spherical robot*

Fig. 1 shows the structure of amphibious spherical robot, the upper hemisphere shell adopts a double-layer seal design, which is equipped with electronic devices such as batteries and controllers. The diameter of the spherical robot is 350mm, the motion part is composed of four feet, each foot has two degrees of freedom [10-20]. The robot experiment platform can be carried out on the road and underwater sports and other functions. The amphibious spherical robot can perform a variety of tasks near the sea and beaches. With the characteristics of flexible movement, high maneuverability and strong adaptability to environment, the environment detection and task execution can be realized under both water and land conditions [21-24]. This paper is based on the underwater pipeline tracking, only the use of spherical robot underwater function.

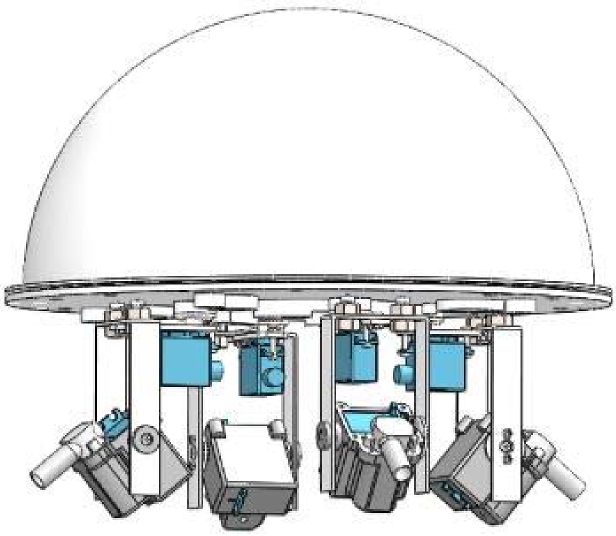


Fig. 1 Amphibious spherical robot

B. *Tracking system*

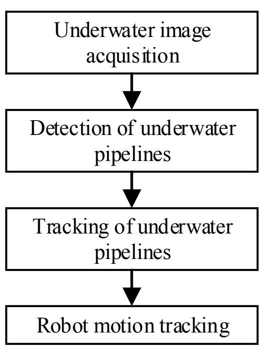


Fig. 2 Process of tracking the system

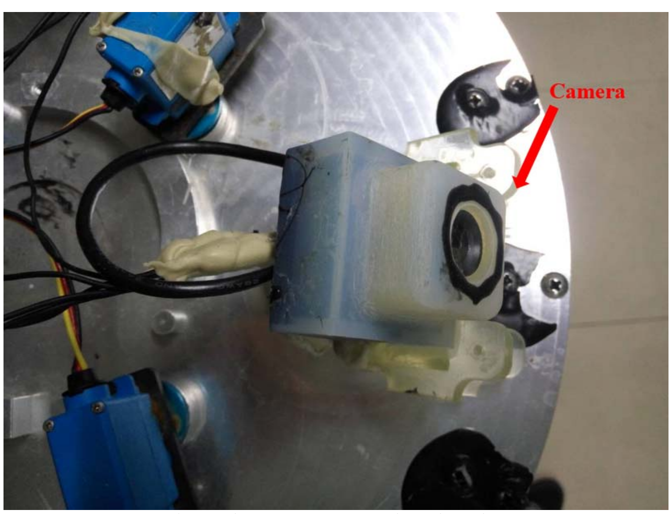


Fig. 3 The camera mounted on the robot

The tracking system consists of an image collector, a motion controller and a spherical robot. As shown in Fig. 2, is the process of tracking the system. The information acquisition of the underwater pipeline image is done by installing the camera in front of the amphibious spherical robot. In this system, the camera is taken with the sealing seal, as shown in Fig. 3, the camera output resolution is 640×480. Due to the need for real-time processing of underwater images, the processor requirements are relatively high, the robot added an image processor. A separate controller is used for the control of a spherical robot. After the image processor completes, the motion controller of spherical robot is controlled by the feedback of the image processor, thereby controlling the movement of the robot.

III. DETECTION OF UNDERWATER PIPELINE IMAGES

The detection of underwater pipeline image includes image gray, image filtering, histogram equalization, image binarization, edge detection and Hough transform. Through image processing, the boundary information of pipeline in image can be get, thereby the detection of underwater pipeline image could be realized. The specific process is shown in the Fig. 4.

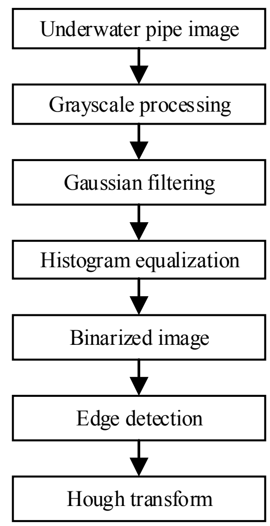


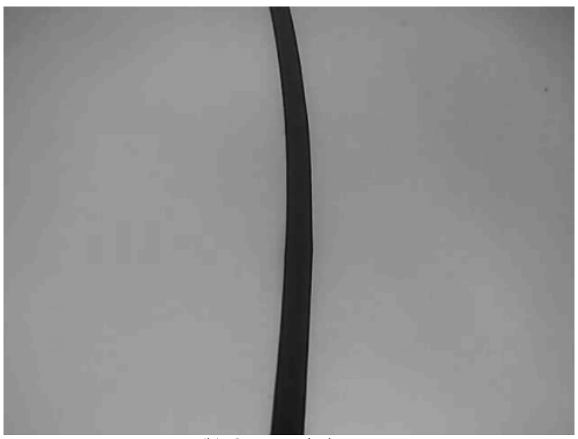
Fig. 4 Process of image detection

A. *Filtering of image*

The image captured by the camera is an image of color information. Because of the large volume of color image information, the direct processing calculation is large and the speed is slow. Though gray images only contain brightness information, the primary information will not lose. So this paper uses the converted gray-scale image for processing. The original image captured by the camera and the gray image obtained after processing is shown in Fig. 5.

Histogram equalization of gray image is made to improve image contrast, and to realize the image enhancement. Because the water has a certain impact on images collected, and underwater images collected by the camera have a lot of noise. The underwater image needs to be filtered. There are a lot of common filtering algorithms, this paper compares several common and effective filtering algorithms, the results are shown in table I. The filtering effect of various methods is shown in Fig. 6. Considering the effect of noise reduction and time consuming, this paper Gaussian filter is selected in this paper.

(a) Original image

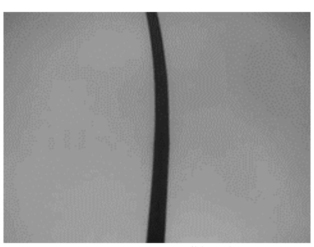


(b) Gray-scale image

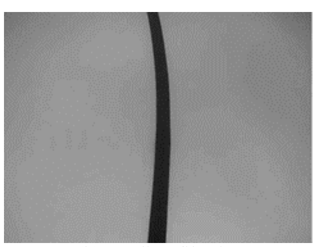
Fig. 5 The original image and gray-scale image

TABLE I
Filtering results of various methods

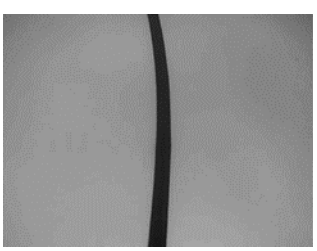
Filtering method	Time (s)	Evaluation results
Low pass	0.0187963	Normal
Median	0.0618361	Good
Gaussian	0.0124468	Good
Bilateral	0.0518607	Better



(a) Low pass filtering



(b) Median filtering



(c) Gaussian filtering

(d) Bilateral filtering

Fig. 6 Filtering effect of various filtering methods

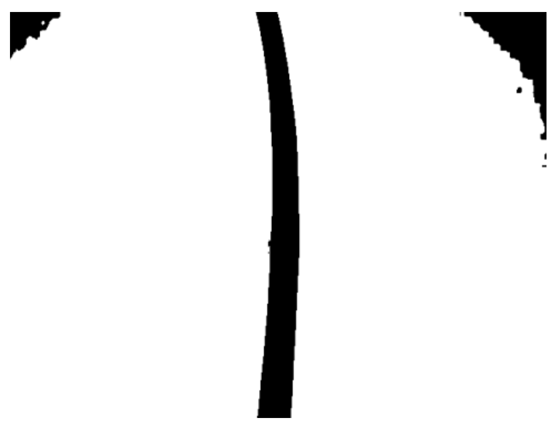
B. Binarization of image

Because there are obvious differences in grayscale between the tracked target and the background, and to better identify the underwater pipeline, the image need to be processed to binary image. Thresholding segmentation converts a gray-scale image into a binary image where the two levels are assigned to pixels that are below or above the specified threshold value. Then underwater pipeline can be identified effectively.

The key to image binarization is the selection of threshold, the core of threshold segmentation method is the criterion function of threshold selection. There are many common threshold segmentation methods, considering the characteristics of underwater pipelines, the threshold method based on histogram region partitioning can be selected to segment the underwater pipeline image.

In this paper, the Otsu method is used to segment the underwater pipeline image. The Otsu method is commonly used.

(a) Otsu



(b) The maximum entropy

Fig. 7 The segmentation effect of the two segmentation methods.

Grayscale image have L grayscale levels, that is $(0,1,\cdots,i,\cdots,L-1)$, and grayscale image of the total number of pixels is $N = n_1 + n_1 + \cdots + n_i + \cdots + n_{L-1}$ .The number of image pixels with a grayscale value of i is n_i , the probability is:

$$P_i = n_i / N \tag{1}$$

The threshold t dichotomizes the pixels into two classes C_0 and C_1, C_0 is composed of pixels between the gray value $[0,t]$, and C_1 is composed of pixels between the gray value $[t+1, L\text{-}1]$, then the probability of C_0 and C_1 is:

$$\omega_0 = \sum_{i=0}^{t} P_i \tag{2}$$

$$\omega_1 = \sum_{i=t+1}^{L-1} P_i \tag{3}$$

The average value of C_0 and C_1 is:

$$\mu_0 = \sum_{i=0}^{t} \frac{iP_i}{\omega_0} \tag{4}$$

$$\mu_1 = \sum_{i=t+1}^{L-1} \frac{iP_i}{\omega_1} \tag{5}$$

The mean value of the whole image is:

$$\mu = \omega_0\mu_0 + \omega_1\mu_1 \tag{6}$$

$$\omega_0 + \omega_1 = 1 \tag{7}$$

$$\partial^2 = \omega_0(\mu_0 - \mu)^2 + \omega_1(\mu_1 - \mu)^2 \tag{8}$$

When ∂^2 is the maximum value, the corresponding t value is the optimal threshold [25].

Another common method is the maximum entropy method. The threshold selection criterion of maximum entropy method is the maximum of the total entropy value of the background class and target class, that is, the maximum amount of information.

The segmentation effect of consumption of the two segmentation methods is shown in the Fig. 7, the results show that the method chosen in this paper is more appropriate.

C. Edge detection and Hough transform of image

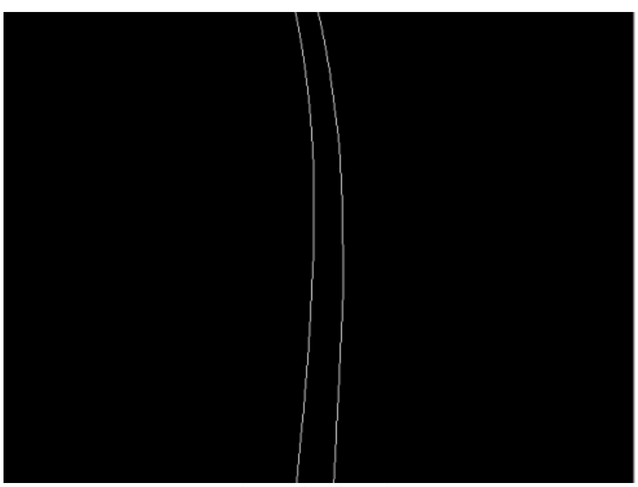


Fig. 8 Edge detection

The detection of pipeline images is realized by detecting the edge of the pipeline. Since the binary image may have holes or isolated points, the image should be corroded and expanded to improve the precision of edge detection. Edge detection is the place where gray scale vary rapidly in the image, and then the boundary of the object is identified. In this paper, the canny operator is applied for edge detection, which utilizing the Gaussian smooth filter convolve with the image, and then use the first derivative to obtain the local maximum, namely the marginal point. The results of edge detection are shown in Fig. 8.

The underwater pipeline has obvious linear characteristics. The Hough transform is used to deal with the line detection of binary image, and the Hough transform is a discrete form of linear parameter transformation. The Hough transform is applied to fit the edge of the underwater pipeline image, and the location information of the pipeline is obtained. The Hough transform under general method is to map the image to its parameter space, the computation amount and the required memory space are relatively large. In this paper, the Probabilistic Hough transform is taken to detect the straight line, reduce the computational amount and the operation time.

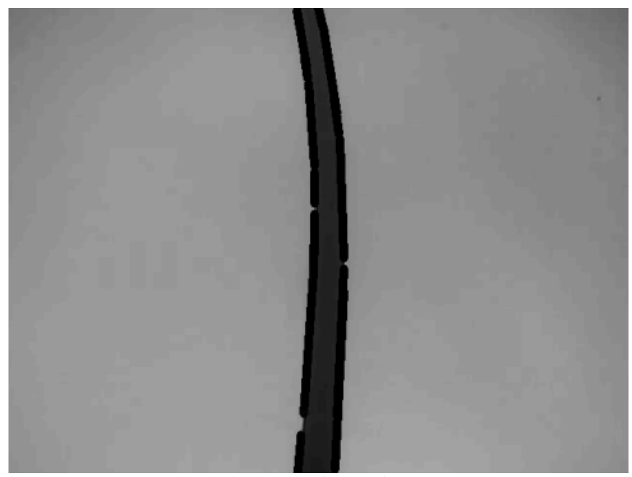


Fig. 9 Hough transform

As shown in the Fig. 9, it is linear fitting of underwater pipeline image by Probabilistic Hough transform.

IV. TRACKING OF UNDERWATER PIPELINES

To improve the accuracy and robustness of underwater pipeline tracking, the Kalman filter is used to track the detected edge information. The PID control algorithm is utilized to control the spherical robot, and the improvement measures are put forward proposed in this paper to realize the tracking of the underwater pipeline.

A. Target tracking based on Kalman filter

Kalman filter is a linear minimum variance estimation algorithm for state sequences of dynamic systems, which is characterized by high noise resistance and strong stability [26]. The Kalman filter is updated with the status data from the previous time and the latest measurements [27]. During the Kalman filter tracking process, the initial assignment is adopted, and the better tracking effect is achieved by adjusting the parameters continuously. Because the deviation of the pipe position of the two-frame image is not too large, the system can trace the pipeline target in the video image sequence with the information of the underwater pipeline.

The state vector of pipeline boundary coordinates is $X(k-1)$ at time $k-1$, and at time k, the state vector of the pipeline boundary is:

$$X(k) = AX(k-1) + W(k) \tag{9}$$

where A the state transition matrix at time k, $W(k)$ is the noise of the system at time k, the noise is assumed to be Gaussian white noise, then the covariance matrix is Q [28].

The measured value of the pipe at time k is:

$$Z(k) = HX(k) + V(k) \tag{10}$$

where H is the measurement matrix and $V(k)$ is the noise measured at time k, assuming that it is Gaussian white noise, then the covariance matrix is R.

Set the status to $X(k-1)$ at time $k-1$, the corresponding covariance matrix is $P(k-1)$. The estimated value at time k is (11). The corresponding error covariance matrix of $\hat{X}(k|k-1)$ is (12).

$$\hat{X}(k|k-1) = AX(k-1) \tag{11}$$

$$\hat{P}(k|k-1) = AP(k-1)A^T + Q \tag{12}$$

The Kalman Gain is (13). The state at time k is (14). The corresponding error covariance matrix of $X(k)$ is (15).

$$K_g(k) = \hat{P}(k|k-1)H^T / (H\hat{P}(k|k-1)H^T + R) \tag{13}$$

$$X(k) = \hat{X}(k|k-1) + K_g(k)(Z(k) - H\hat{X}(k|k-1)) \tag{14}$$

$$P(k) = (1 - K_g(k)H)\hat{P}(k|k-1) \tag{15}$$

In the iterative process, the Kalman gain is calculated, and the resulting new state $X(k)$ and the corresponding error covariance matrix $P(k)$ are taken as inputs to the next moment.

B. *Control scheme*

The key to underwater pipeline tracking is to observe the location and direction of the pipeline relative to the current heading of the underwater vehicle. For the tracked pipeline, the angle between the latest part of the pipeline and the robot heading is calculated, that is, the angle between the vertical direction of the pipe and the image is computed on the acquired image. To track the pipeline, it cannot rely on the deflection angle of the pipeline, but also need to know the distance from the robot heading direction, this paper draws a picture of the vertical centerline of the center of the image that collected by the camera, which can get the distance between the newest trajectory line and the centerline of the pipeline. Through computing the angle and distance of the pipeline deviating from the course, the PID control algorithm is used to control the spherical robot, and the real-time tracking of the underwater pipeline is realized.

V. EXPERIMENTS AND EVALUATION

In order to demonstrate the effectiveness of the proposed underwater pipeline tracking system, some experiments were carried out in a pool of 2.87m×2.01m×1.00m. In the pipeline tracking experiment, the depth of the spherical robot is constant from the underwater pipeline, and the water pipe is used to simulate the underwater pipeline. The Low-speed pipeline tracking experiment is carried out under the condition of static flow and flowing flow respectively. The effect diagram of the spherical robot tracking the underwater pipeline is shown in Fig. 10.

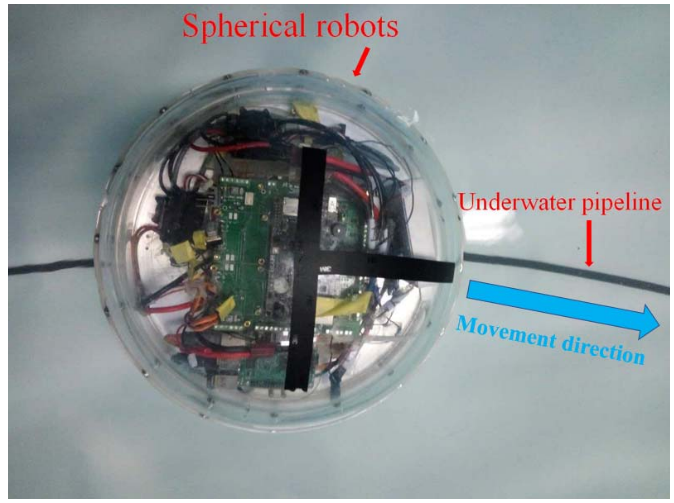


Fig. 10 Underwater pipeline tracking experiment in the pool

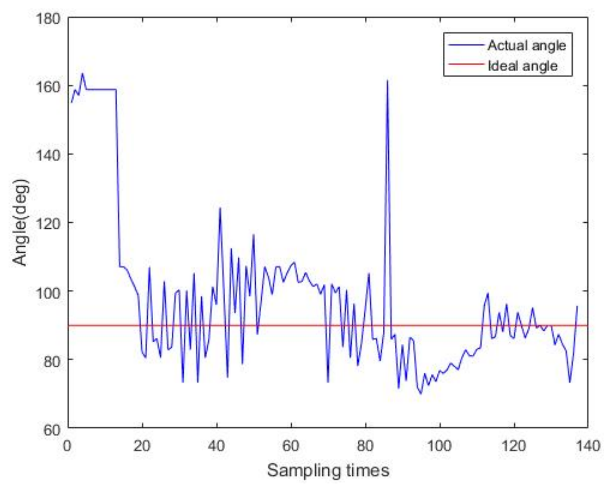


Fig. 11 Actual and ideal value of the underwater pipeline for the robot

In this paper, the actual angle and ideal value of the underwater pipeline for a spherical robot is shown in Fig. 11. The angle of the spherical robot moving forward is 90 degrees, and the underwater spherical robot has a high accuracy in the extraction and recognition of the pipeline. Due to the delay of the movement of the spherical robot, the spherical robot will be partially deviated in the process of pipeline tracking, but that does not affect the implementation of underwater pipeline tracking.

VI. CONCLUSIONS AND FUTURE WORK

This paper presents the identification and tracking method of underwater pipelines for underwater spherical robots. Firstly, the process of capturing underwater images collected by the camera is described, and the underwater image was collected by a 2D camera, the edge information of the pipeline was detected by the image processing algorithm. Secondly, the edge of the pipeline was tracked by the Kalman filter and the control quantity is given to the movement controller of the spherical robot. And then, the control of spherical robots was achieved through the PID control algorithm. Finally, some experiments were carried out in a pool, and the identification and tracking of underwater pipeline was realized. Experimental results showed that the system has certain reliability, which can meet the engineering requirements. Follow-up studies will consider the movement state of the underwater robot when the pipeline is lost during the tracking process.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China (61503028, 61375094), and Excellent Young Scholars Research Fund of Beijing Institute of Technology (2014YG1611). This research project was also partly supported by National High Tech. Research and Development Program of China (No.2015AA043202).

REFERENCES

[1] C. Chen, M. Nakajima, “Study on pipe-soil interaction during lateral buckling of pipelines unburied in deepsea”, *Tianjin University*, pp.1-13, 2014.

[2] S. Bazeille, I. Quidu, L. Jaulin, “Identification of underwater man-made object using a colour criterion”, *Conference on Detection and Classification of Underwater Targets*, pp.45-52, 2007.

[3] W. Zhu, Y. Xu, Z. Qin, “Underwater image segmentation based on particle swarm optimization and fuzzy partition entropy”, *Optical Technique*, vol. 33, no. 5, pp. 754-759, 2007.

[4] X. Tang ,Y. Pang , H. Zhang , W. Zeng , Y. Li, “Underwater pipeline detection by AUV based on monocular vision”, *Robot*, vol. 32, no. 5, pp. 592-600,2010.

[5] P. Drews-Jr, V. Kuhn, S. Gomes, “Tracking System for Underwater Inspection Using Computer Vision”, *International Conference on Offshore and Marine Technology: Science and Innovation*, pp. 27-30, 2012.

[6] S. Krupinski, G. Allibert, M. K. Hua, and T. Hamel, "Pipeline tracking for fully-actuated autonomous underwater vehicle using visual servo control", *American control conference2012*, pp. 6196-6202, 2012.

[7] C. Berger, M. A. Jordán, J. L. Bustamante , E. Trabes, " A vision-based controller for path tracking of autonomous underwater vehicles", *15th Argentine Symposium on Technology*, pp.13-24, 2014.

[8] Z. Ji, “Application of Underwater Linear Objects Processing Algorithm in Submarine Pipeline Inspection Robot”, *Ocean University of China*, pp.1-45, 2015.

[9] B. Gao, “The application of computer digital image technology in detection of AUV underwater pipeline”, *Electronic Test*, pp.164-166, 2015.

[10] S. Guo, Y. He, L. Shi, S. Pan, R. Xiao, P. Guo, “Modal and fatigue analysis of critical components of an amphibious spherical robot”, *Microsystem Technologies*, pp. 1-15, doi: 0.1007/s00542-016-3083-0, 2016.

[11] S. Guo, S. Pan, L. Shi, et al, “Visual Detection and Tracking System for an Amphibious Spherical Robot”, *Sensors*, vol.17, no.4, pp.1-21, 2017.

[12] L, Shi, S, Pan, K. Tang, et al, “Design and evaluation of quadruped gaits for amphibious spherical robots”, *Proceedings of the 2016 IEEE International Conference on Robotics and Biomimetics Qingdao*, pp.13-18, 2016.

[13] Y. He, S. Guo, L. Shi, et al, “Dynamic Gait Analysis of a Multi-functional Robot with Bionic Springy Legs”, *Proceedings of 2016 IEEE International Conference on Mechatronics and Automation*, pp.689-694, 2016.

[14] C. Yue, S. Guo, L. Shi, “Hydrodynamic Analysis of the Spherical Underwater Robot SUR-II”, *International Journal of Advanced Robotic Systems*, vol.10, no.3, pp.1–12, 2013.

[15] S. Pan, S. Guo, L. Shi, Y. He, Z. Wang and Q. Huang, "A spherical robot based on all programmable SoC and 3-D printing", *Proceedings of 2014 IEEE International Conference on Mechatronics and Automation*, pp.150-155, 2014.

[16] S. Guo, S. Mao, L. Shi, et al, “Development of an amphibious mother spherical robot used as the carrier for underwater microrobots”, *Proceedings of 2012 ICME International Conference on Complex Medical Engineering*, pp.758–762, 2012.

[17] M. Li, S. Guo, H. Hirata, H. Ishihara, “Design and performance evaluation of an amphibious spherical robot”, *Robotics and Autonomous Systems*, vol. 64, pp. 21-34, 2015.

[18] Y. He, L. Shi, S. Guo, S. Pan, Z. Wang, “Preliminary mechanical analysis of an improved amphibious spherical father robot”, *Microsystem Technologies*, pp. 1-16, doi: 0.1007/s00542-015-2504-9, 2015.

[19] L. Shi, S. Guo, S Pan, et al, “A multifunctional underwater microrobot for mother-son underwater robot system”, *Proceedings of 2013 IEEE International Conference on Robotics and Biomimetics*, pp.1007–1012, 2013.

[20] Y. He, L. Shi, S. Guo, S. Pan, Z, Wang, “3D Printing Technology-based an Amphibious Spherical Underwater Robot”, *Proceedings of 2014 IEEE International Conference on Mechatronics and Automation*, pp. 1382-1387, 2014.

[21] S. Pan, L. Shi, S. Guo, "A Kinect-Based Real-Time Compressive Tracking Prototype System for Amphibious Spherical Robots", *Sensors*, vol. 15, no. 4, pp. 8232-8252, 2015.

[22] Y. Li, S. Guo, C. Yue, “Preliminary Concept of a Novel Spherical Underwater Robot”, *International Journal of Mechatronics and Automation*, vol.5, no.1, pp. 11-21, 2015.

[23] C. Yue, S. Guo, L. Shi, “Design and Performance Evaluation of a Biomimetic Microrobot for the Father-son Underwater Intervention Robotic System”, *Microsystem Technologies*, vol.22, no.4, pp. 831-840, 2015.

[24] L. Shi, S. Guo, S. Mao, C. Yue, M. Li, K. Asaka, “Development of an Amphibious Turtle-Inspired Spherical Mother Robot”, *Journal of Bionic Engineering*, vol.10, no.4, pp. 446-455, 2013.

[25] X. Yuan, H. Jiang, Y. Chen, X. Wang, “Extraction of Water Body Information Using Adaptive Threshold Value and OTSU Algorithm”, *Remote Sensing information*, vol.31, no.5, pp. 36-42, 2016.

[26] K. Guo, Y. Wang, X. Guo, “Lane Detecting and Tracking Algorithm with Noise Analysis of Kalman Filter”, *Computer Measurement & Control*, vol.24, no.5, pp. 216-219, 2016.

[27] F. Liu, S Zhang, W. Zhu, Z. Li, “A Vision-Based Lane Detection and Tracking Algorithm”, *Journal of Tongji University Natural science*, vol.38, no.2, pp. 223-229, 2010.

[28] T. Chen, H. Zhang, D. Chen, C. Tan, “Lane Detection Based on High Priority Pixels and Tracking by Kalman Filter”, *Automotive Engineering*, vol.38, no.2, pp. 200-205, 2016.