Proceedings of 2018 IEEE
International Conference on Mechatronics and Automation
August 5 - 8, Changchun, China

Binocular Camera-based a Docking System for an Amphibious Spherical Robot

Shuxiang Guo[1,2,3], Yu Liu[1,2], Liwei Shi[1,2*], Ping Guo[1,2], Huiming Xing[1,2], Xihuan Hou[1,2], Zhan Chen[1,2], Shuxiang Su[1,2], Huikang Liu[1,2]

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

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

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

guoshuxiang@bit.edu.cn, liuyuydbby@163.com, shiliwei@bit.edu.cn

* Corresponding author

***Abstract* - In order to fulfill the task about autonomous recovery and charging of robots, a set of robotic docking system based on binocular stereo vision was initially designed and implemented. A binocular camera was used in our docking system. Through the image captured by binocular camera of the surrounding environment, we can obtain the two kinds of image, which include color image and depth image. And in order to get accurate depth information, we conducted a binocular camera calibration experiment. Then according to the depth information, the robot recognize the docking receptacle also as a marker fixed in the pool, then using KCF (Kernelized Correlation Filters) algorithm to track the target and making robot arrive the docking destination accurately. The docking system can be implemented by the process above. During the experiment, we selected the receptacle in the image, the robot recognized target and arrived at the designated location. The experimental results demonstrated the veracity and robustness of the proposed docking system based on binocular stereo vision.**

Index Terms – Amphibious Spherical Robot. Binocular Camera. Docking System. Visual Tracking.

I. INTRODUCTION

The development of applications such as the promotion of amphibious resource exploration, autonomous search and rescue, and the long-term monitoring of the environment in the coastal transitional environment has always been a hot topic. Completing research and rescue missions for robots in earthquakes and other natural disasters, as well as research on sampling of abundant underwater resources also have received much attention. For this application, amphibious robots have been widely used [1]-[5]. Robotic autonomous docking refers to the process that autonomous movement of mobile robot to a specific pose and orientation. It is the most important part to achieve the self-charging, and it also make robotic recovery easy. In many applications, the robot needs to complete the docking before it achieve the specified task. Allowing the robot to go to the station for docking autonomously is a key link to solve the issue of energy autonomy and has important military and civilian values. This paper studies the autonomous docking of amphibious spherical robots based on binocular vision in indoor environment.

Nowadays, research on the docking system using various homing sensors and techniques for the underwater robot has been done worldwide [6]-[14]. A docking guidance system was designed and implemented using the Sugeno fuzzy inference system (FIS) in [7]. Electromagnetic Homing (EM) system was proposed and tested in [8] for docking experiments. In [9], the AUV homes to the dock using an ultrashort base line (USBL) sonar transceiver mounted in the vehicle nose. In this work, dual-eyes camera is used for visual-servo in docking experiment rather than using combination of other sensors. In 2015, Myo Myint et al [15] proposed an underwater docking experiments, demonstrating the automatic charging in underwater, with regulating performance of the underwater robot using visual-servo by dual-eyes camera. In Harbin Engineering University, Ye Li et al [16] an attempt research of vision guided docking algorithm using two cameras is carried on considering the relatively short range of vision at sea. In paper [17], proposed a new solution for autonomous charging of a robotic fish through a novel claw mechanism for docking guidance and direct contact. In these research, different sensors were used to obtain the location of the target. However, these sensors perform poorly in terms of accuracy and real-time performance, and they are bulky and not suitable for being mounted on small-sized robots. Therefore, we proposed a docking system based on binocular camera rather than other using combination of sensors for proposed robot.

Aiming at vision-based amphibious spherical robot, a binocular camera-based docking system was designed and implemented. Our main research content of these paper are 1) briefly introduce the structure and performance of the improved amphibious spherical robot and detailed description of the binocular camera and its waterproof structure mounted on the amphibious spherical robot, 2) conduct binocular camera calibration experiments to accurately obtain target depth information and perceive the surrounding environment better, 3) analyze the mathematical principle of binocular stereo vision to recognize the objective precisely by depth information, then using KCF algorithm to track the target and making robot reach the docking location accurately, 4) control strategy of system is presented. So, the docking system of our robots can be implemented. We conducted regulated

performance experiments to verify the performance of the docking system in an indoor pool, which size is 3.81×2.01×1.00m^3. It is shown experimentally that the proposed system is stable to physical disturbances given by external forces to the amphibious spherical robot. Finally, docking experiment underwater docking is implemented using proposed method, having approved its robustness against disturbances and its usefulness.

The structure of this paper is organized as follows. In section II, the structure of amphibious spherical robot and the calibration experiment of camera are introduced. Docking system based binocular camera is described in section III, also conclude establishment for docking system and control strategy. The experimental results are provided in section IV. Finally, section V presents some conclusions and future work.

II. Related Work

A. The Structure of an Amphibious Spherical Robot

Based on the amphibious spherical robotic platform introduced in the reference [18]-[22], we have developed a new generation of amphibious spherical robots in last year. Fig.1 shows the overview structure of our new amphibious spherical robot. The appearance of the robot is a spherical structure and its diameter is 300mm, it is divided into two parts by an aluminium alloy circular plate in the middle of the sphere. The upper hemisphere consists of two parts. The upper part of the hull is a water inlet and outlet tank. Sonar sensor and binocular camera are included in the tank. The lower part is a sealed hull, in which includes the circuit module like controllers and a variety of sensors such as pressure sensor and depth sensor. The lower hemisphere consists of two quarter-hulls driven by two servos to open or close the quarter-hulls. In the lower hemisphere, sealed waterproof battery compartment and four actuating units are mainly symmetrical installed on the aluminium alloy circular plate. Three waterproof servos and a water-jet thruster form an actuating also called robotic leg shown in Fig.1. Each mechanical leg has two degrees of freedom, so it can achieve horizontal and vertical motions.

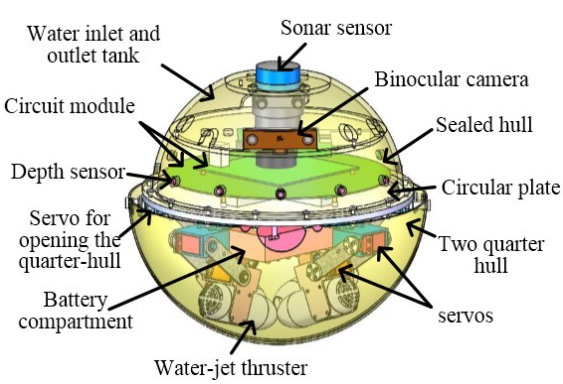

Fig.1. Structure of the proposed amphibious spherical robot

B. Binocular Camera and Calibration

In this section, the characteristics of binocular camera on our amphibious spherical robot and the waterproof structure are introduced. Then the extrinsic calibration algorithm [23] used by the proposed system is briefly reviewed. The dynamic target detection and location of mobile robots based on binocular stereo vision is one of the leading topics in the field of machine vision. Binocular stereo vision imitates human using of binocular to acquire two two-dimensional images to perceive three-dimensional information, so as to calculate the depth information of the target object in the space scene. The binocular camera used on our amphibious spherical robot for detection equipment is RER-DCAM-1MP, which captures the 720p, 640×320 color image at 60 frames per second(fps), and its perspective is 105°. A waterproof cover was machined using the 3D printing technology, and two pieces of optical glasses are fixed in front of the camera lens as shown in Fig.2.

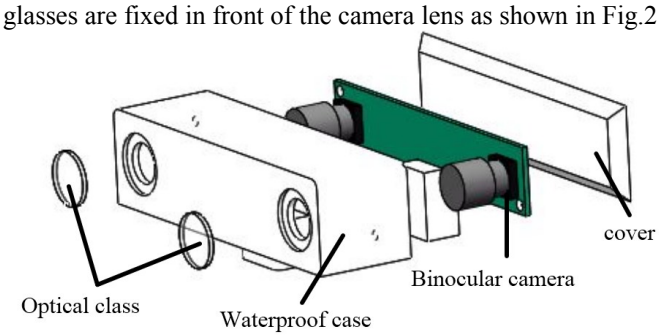

Fig.2. Struction of waterproof binocular camera

In order to effectively utilize the data from the binocular camera, it is important to determine their relative position and orientation from each other, which affect the geometric interpretation of its measurements. The internal and external parameters should be acquired. Using camera calibration, we can convert world coordinates P_w= [x_w, y_w, z_w] to image coordinates P_i=[u,v] by formula as Equation (1):

$$P_i \approx K\left(RP_W + T\right) \tag{1}$$

Where K is the camera's 3 × 3 intrinsic matrix, R is a 3 × 3 matrix indicating the orientation of the camera, and T is a 3 × 1 vector corresponding to its position. To get these parameters, a calibration experiment was conducted in a pool. The distance between chessboard and camera was adjusted with different poses of the chessboard and a wide range of orientation to reduce the extrinsic calibration errors. Finally, the rotating matrix R and translation vector can be derived as Equations (2) and (3):

$$R = \begin{pmatrix} 1.0000 & -0.0032 & -0.0078 \\ 0.0031 & 0.9999 & -0.0110 \\ 0.0078 & 0.0110 & 0.9999 \end{pmatrix} \tag{2}$$

$$T = \begin{pmatrix} -62.0425 & 0.0518 & -0.2430 \end{pmatrix} \tag{3}$$

III. Binocular Camera-Based Docking System

Binocular are two cameras for video capture of the same target, they have the same ability as the human vision to calculate the target depth information. This chapter analyzes the problem of mutual conversion of computer binocular

vision in world coordinates and image coordinates, and establishes a binocular model. Then the tracking algorithm and the control strategy of docking system for out robot are introduced.

A. Binocular Camera Stereo Vision System

Binocular stereo vision imitate people's binoculars to obtain environmental information, and to obtain outside world information through two parallel cameras. The two cameras observe the same object from different viewpoints, and form an imaging point on the left and right imaging planes. The difference of pixel between the same object in the two images is used to obtain the disparity value and depth value. The principle of stereoscopic parallax can be used to calculate the pose information of the object in the environment. As shown in Fig.3, the schematic imaging of binocular stereo vision, P is any point in space. The point P_1 is the imaging point of point P in the left imaging plane, and the point P_2 is the imaging point in the right. There are four coordinate systems in our model establishment of binocular camera stereo vision, they are pixel, image, camera and world coordinate system. The conversion process among them is shown in Fig.4. And the location diagram among them is shown in Fig.5.

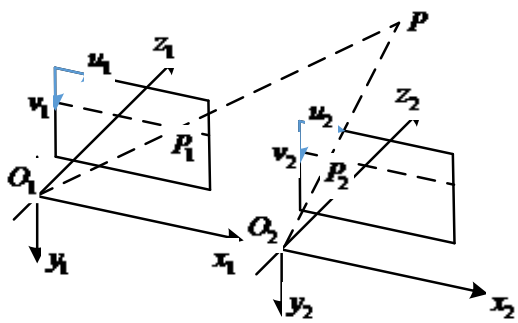

Fig.3. Schematic imaging of binocular stereo vision

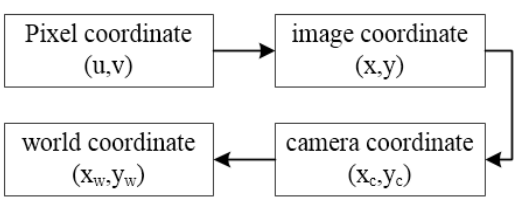

Fig.4. Coordination systems conversion

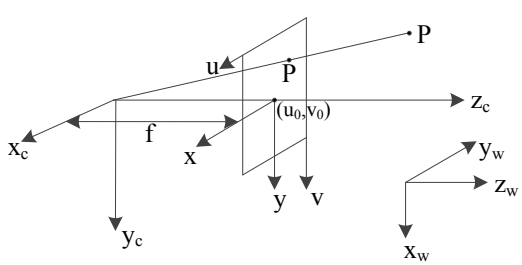

Fig.5. Location diagram among coordination systems

In Fig.5, an any point in space P, its world coordination is (x_w, y_w, z_w), camera coordination is (x_c, y_c), image coordination is (x, y) and pixel coordination is (u, v). We can easily get the values of u and v, than the values of x and y are obtained by Equations (4) and (5):

$$u = \frac{x}{dx} + u_0 \tag{4}$$

$$v = \frac{y}{dy} + v_0 \tag{5}$$

Here, d_x and d_y respectively represent the number of pixels per millimetre. The matrix of this formula is shown as Equation (6):

$$\begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = \begin{pmatrix} 1/dx & 0 & u_0 \\ 0 & 1/dy & v_0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \tag{6}$$

To determine the coordinates of the point P in the camera coordinate system, the coordinates of the P point in the image coordinate system need to be converted. Based on the triangle similarity principle, we can get the conversion formula as Equation (7):

$$\begin{aligned} \frac{x_l}{x_c} &= \frac{f}{z_c} & x_c &= \frac{B \bullet x_l}{x_l - x_r} \\ \frac{x_r}{y_c - B} &= \frac{f}{z_c} & \Rightarrow y_c &= \frac{B \bullet y}{x_l - x_r} \\ \frac{y}{y_c} &= \frac{f}{z_c} & z_c &= \frac{B \bullet f}{x_l - x_r} \end{aligned} \tag{7}$$

Where x_l and x_r represent the abscissa of the imaging point of the spatial point P in the left and right planes, B is the distance between two optical axises, and f is the focal length. So, the key of the obtaining the value of x_c, y_c, z_c is to calculate the value of x_l-x_r, which called disparity. As long as the disparity value is accurately calculated, the coordinates of the P point in the camera coordinate system can be obtained.

At present, we have obtained the coordinates of the point P in the camera coordinate system, and then we need to convert the point P to the coordinates in the world coordinate system. This conversion relationship can be described by the orthogonal unit rotation matrix R and the three-dimensional translation vector T. R is the direction of the world coordinate system relative to the camera coordinate system, and T is the distance of the world coordinate system relative to the camera coordinate system. R and T don't related with the camera, so these two parameters are called extrinsic parameters. We have derived matrix R and vector T in last part. Its conversion formula is shown as Equation (8):

$$\begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix} = R \begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} + T \tag{8}$$

From the above steps, we can conclude that after acquiring any point P in the space with the binocular camera, the

coordinates of the P point in the world coordinate system can be obtained by the mutual transformation between the coordinate systems.

B. Visual-Tracking Algorithm

Target tracking algorithm has always been a hot area of research [24]. Its main purpose is to analyze video, complete the identification and tracking of the target. The tracking algorithm captures the trajectory of the target and obtains target operating information. The docking system of our robot must not only use the algorithm to track the target, but also need to calculate the location of the target and other information. At this time, we need to use the tracking algorithm combined with the ability of binocular vision measurement, while maintaining the tracking algorithm that can lock the target object, calculate the target corresponding feature points and calculate the three-dimensional coordinate information of the tracked object through the binocular vision model.

Considering the practical application requirements of amphibious spherical robots, it is necessary to make a compromise between processing accuracy and real-time performance when design the tracking algorithms. Recently, many people have studied different real-time tracking algorithms, such as Staple[25], L1-tracker[26] and FCT[27]. However, due to the existence of drift[28], the robustness and long-term tracking performance of these algorithms are not ideal. In 2015, Henriques et al [29] putted forward a KCF (Kernelized Correlation Filters) algorithm with high tracking accuracy and excellent real-time performance, which lays the foundation for designing real-time tracking of robots.

KCF is a discriminative tracking method. Such methods usually train a target detector during the tracking process, use the target detector to detect whether the next frame is the target, and then use the new result of detection to update the training set. Then update the target detector. In the training of the target detector, the target region is generally selected as a positive sample, and the target's surrounding region is a negative sample. Of course, the more likely the region closer to the target is a positive sample. Positive and negative samples are collected using the circulant matrix of the area around the target, and the target detector is trained using ridge regression, and the circulant matrix can be successfully used to transform the operation of the matrix into the Hadamad product of the vector, the element can be diagonalized in the Fourier space. The point multiplication greatly reduces the amount of computation, improves the speed of operation, and allows the algorithm to meet real-time requirements.

C. Control of Docking System

From the previous section, we can get the coordinates of the centroid of the receptacle in image captured by the camera. Although the docking receptacle is stationary with respect to the ground, the robot is moving in real time, so the center of mass of the target also changes in real time. Therefore, we need to control the yaw angle of robot underwater so that the center of mass of the receptacle can always at the center of the imaging area of the camera. Then according to the depth value and position information of the target measured by the binocular camera, the yaw angle of deflation can be derived by Equation (9):

$$\theta = \arctan(x/z) \tag{9}$$

Then the robot is driven to reach the vicinity of the receptacle through the water-jet thruster in robot's legs in different directions. At about 20cm, the water-jet thruster in the leg sprays water backwards to stop the robot and complete the docking. The flow chart as shown in Fig.6.

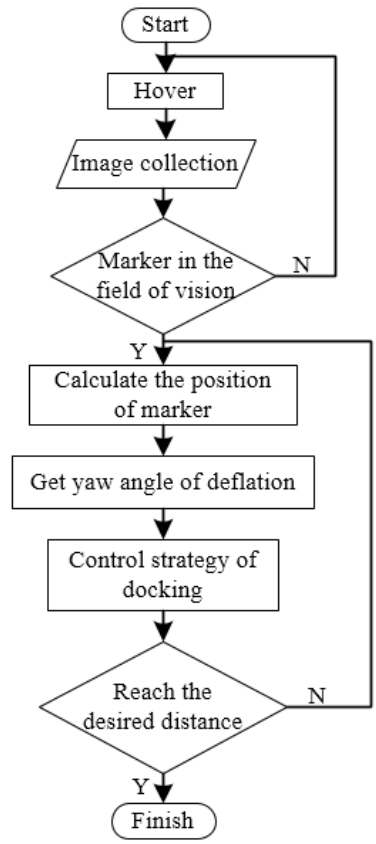

Fig.6. Flow diagram of docking system

The motion of the robot was controlled by the position of the docking receptacle in the field of vision and the distance between the receptacle and the robot, as presented in Table I. When it is detected that the receptacle is not in the center of the robotic field of vision, and the distance between them is not equal to 20 cm, the robot will perform different movements for achieving this purpose by adjust its yaw angle. The yaw angle of the robot is mainly controlled through the four water-jet thrusters to achieve forward, backward, left and right turns. And the yaw control strategy diagram of is shown in Fig.7. The dark blue arrow indicates the direction of robotic motion, and the red arrow represents the spray direction of the water-jet thruster. The strength of the spray was indicated by the thickness of the arrow. In the process of linear motion, the two spray motors spray water in the opposite direction to keep the body balance in the horizontal direction. The remaining two

water-jet thrusters have the opposite spray direction and the same spray strength. In the turning movements, special movements in different directions are realized by the water-jet thruster differentially intensity of spraying water.

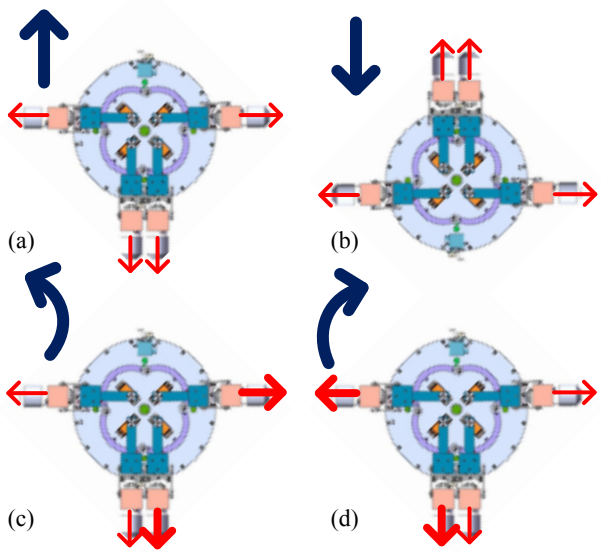

Fig.7. Yaw control strategy diagram of the proposed robot: (a) go forward, (b) go backward, (c) turn left and (d) turn right.

TABLE I
CONTROL STRATEGY OF DOCKING SYSTEM

	Distance value(cm)	
Position in image	>20	<20
Left(θ >0)	Turn left + go ahead	Turn left
Right(θ <0)	Turn right + go ahead	Turn right

IV. EXPERIMENTS AND RESULTS

A. Experimental Setup

To demonstrate the effectiveness, robustness and assess the feasibility of docking system, a series of experiments was conducted in an indoor pool measured 2.81×2.01×1.00m^3 and a global camera used to capture experimental scene was fixed directly above the water surface. The docking receptacle was mounted in the water pool. Robot received image information and control signals through the optical fiber connected to PC as shown in Fig.8. As the evaluation method of the system, we recorded the coordinate value of the target object in the camera field of view and its depth value.

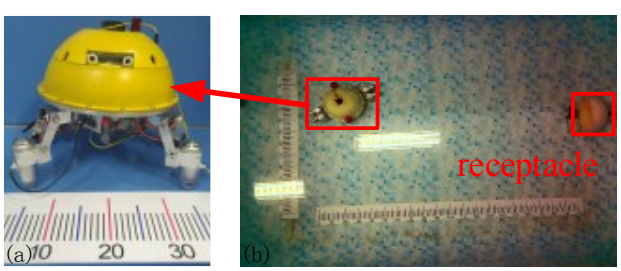

Fig.8. The prototype of our robot and experimental setup: (a) the prototype of the proposed robot and (b) the experimental setup.

B. Experimental results

Binocular camera-based docking system components as shown in Fig.8. Approaching step, in which the speed of robot is low, means the state until the underwater robot recognized the receptacle assuming that the object is presented in front of robot. In other words, our robot does not know the relative pose to the object in the initial condition, and then go forward and transits to a state of visual servoing after discovered the object. We recorded the coordinates of the trajectory of the receptacle in the robotic field of vision, the result shown in Fig.9. The red line represents the coordinates of center in the image, while the black line is the coordinates of the receptacle. From the figure we can see that the robot will continue to approach the receptacle after the yaw angle of the robot controlled by vision. Finally the receptacle will be located in the center of the field of view in the x axis direction. The distance value between docking receptacle and robot is shown in Fig.10. Due to the disparity and depth information calculated by binocular camera, there is a certain amount of error, which is occasionally unstable. Therefore, in the process of docking system by visual servoing, there were some errors, but the overall trend and the final results meet the requirements. With the movement of the robot, the distance between the robot and the receptacle is continuously shortened, and the distance between them is reduced to about 20 cm to complete the docking process. In other words, it can be confirmed that the robot can achieve docking experiment effectively using the proposed system.

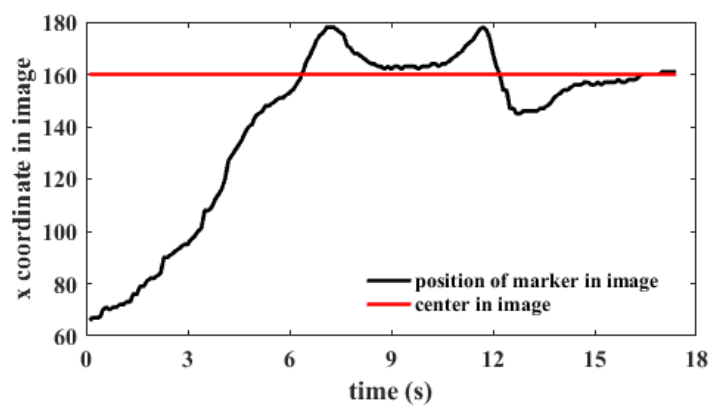

Fig.9. X coordinate values of the receptacle in the field of vision

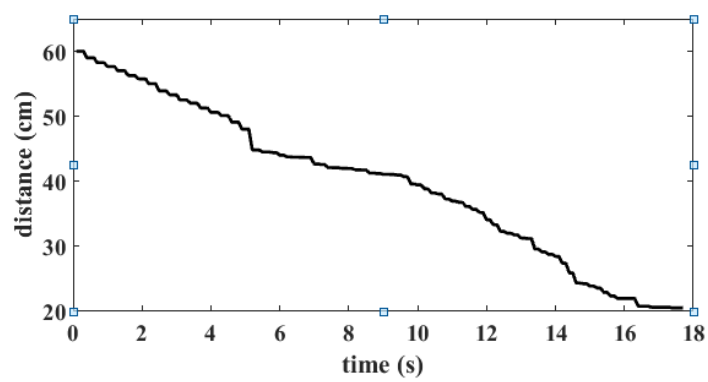

Fig.10. Distance value between receptacle and robot

V. Conclusions And Future Work

Aiming at vision-based amphibious spherical robot, a binocular camera-based docking system was designed and implemented in this paper. Firstly, the overview of amphibious spherical robot and the structure of binocular camera as the most important sensor were introduced. And then the KCF-tracker based docking system of our robot and the control strategy of this system was proposed. Finally, we conducted the experiment in our indoor poor, the accuracy and robustness of docking system were demonstrated.

In the future, we will focus on development of underwater automatic charging system based on our docking system. The following two conditions under what should be taken into consideration in future docking research. Improvements in identifying target objects: Turning objects identified by the robot into lights in the docking system easily to recognize targets in under-illuminated underwater environments, so that it can be used in the ocean. Secondly, optimizing target recognition and tracking algorithm to improve robustness and the capability of anti-interference, also accomplish automatic docking system.

Acknowledgment

This research is partly supported by the National High Tech. Research and Development Program of China (No.2015AA043202), National Natural Science Foundation of China (61773064, 61503028) and Graduate Technological Innovation Project of Beijing Institute of Technology (2018CX10022).

References

[1] S. Guo, Y. He, L. Shi, S. Pan, R. Xiao, and P. Guo, "Modal and fatigue analysis of critical components of an amphibious spherical robot," *Microsystem Technologies*, vol.23, no.6, pp.1-15, 2016.

[2] Y. He, L. Shi, S. Guo, S. Pan, and Z. Wang, "Preliminary mechanical analysis of an improved amphibious spherical father robot," *Microsystem Technologies*, vol.22, no.6, pp. 1-16, 2016.

[3] L. Shi, R. Xiao, S. Guo, P. Guo, S. Pan, and Y. He, "An attitude estimation system for amphibious spherical robots," in *Proceedings of IEEE International Conference on Mechatronics and Automation*, pp. 2076-2081, 2015.

[4] M. Li, S. Guo, H. Hirata, and H. Ishihara, "A roller-skating/walking mode-based amphibious robot," *Robotics and Computer-Integrated Manufacturing*, vol. 44, pp. 17-29, 2017.

[5] C. Yue, S. Guo, and 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.

[6] S. Cowen, S. Briest and J. Dombrowski, "Underwater Docking of Autonomous Undersea Vehicle using Optical Terminal Guidance," *IEEE Journal of Oceans Engineering*, vol.2, pp.1143-1147, 1997.

[7] K. Teo, B. Goh, and O. Chai, "Fuzzy Docking Guidance Using Augmented Navigation System on an AUV," *IEEE Journal of Oceans Engineering*, vol. 37, no.2, 2015.

[8] M. Feezor, F. Sorrell, P. Blankinship, and J. Bellingham, "Autonomous Underwater Vehicle Homing/Docking via Electromagnetic Guidance," *IEEE Journal of Oceans Engineering*, vol.26, no.4, pp.515-521, 2001.

[9] R. McEwen, B. Hobson, L. McBride, and J. Bellingham, "Docking Control System for a 54-cm-Diameter (21-in) AUV," *IEEE Journal of Oceanic Engineering*, vol.33, no.4, pp.550- 562, 2008.

[10] K. Teo, E. An and P. Beaujean, "A robust fuzzy autonomous underwater vehicle (AUV) docking approach for unknown current disturbances," *IEEE Journal of Oceanic Engineering*, vol.37, no.2, pp.143-155, 2012.

[11] J. Park, B. Jun, P. Lee, F. Lee and J. Oh, "Experiment on Underwater Docking of an Autonomous Underwater Vehicle 'ISimI' using Optical Terminal Guidance," *IEEE Oceanic Engineering*, pp 1-6, 2007.

[12] A. Negre, C. Pradalier and M. Dunbabin, "Robust vision-based underwater homing using self similar landmarks," *Journal of Field Robotics*, vol.25, pp.360-377, 2008.

[13] M. Dunbabin, B. Lang and B. Wood, "Vision-based Docking Using an Autonomous Surface Vehicle," in *Proceeding of IEEE International Conference on Robotics and Automation*, pp.25-32, 2008.

[14] P. Batista, C. Silvestre, and P. Oliveira, "A Two-step Control Strategy for Docking of Autonomous Underwater Vehicles," in *Proceeding of American Control Conference*, vol.50, pp.5395-5400, 2012.

[15] M. Myint, K. Yonemori, A. Yanou, and M. Minmami, "Visual-servo-based autonomous docking system for underwater vehicle using dual-eyes camera 3D-pose tracking," *IEEE International Symposium on System Integration*, pp.989-994, 2015.

[16] Y. Li, Y. Jiang, J. Cao, B. Wang and Y. Li, "AUV docking experiments based on vision positioning using two cameras," *Ocean Engineering*, vol.110, pp.163-173, 2015.

[17] P. Phamduy, J. Cheong, and M. Porfiri, "An Autonomous Charging System for a Robotic Fish," *IEEE/ASME Transactions on Mechatronics*, vol.21, no.6, pp.2953-2963, 2016.

[18] H. Xing, S. Guo, L. Shi, S. Pan, Y. He, K. Tang, S. Su, and Z. Chen, "Kalman Filter-based navigation system for the Amphibious Spherical Robot," in *Proceeding of IEEE International Conference on Mechatronics and Automation*, pp.638-643, 2017.

[19] K. Tang, L. Shi, S. Guo, S. Pan, H. Xing, S. SU, P. Guo, Z. Chen, and Y. He, "Vision locating method based RGB-D camera for amphibious spherical robots," in *Proceeding of IEEE International Conference on Mechatronics and Automation*, pp.1509-1514, 2017.

[20] L. Shi, Z. Chen, S. Guo, P. Guo, Y. He, S. Pan, H. Xing, S. SU, and K. Tang, "An underwater pipeline tracking system for amphibious spherical robots," in *proceeding of IEEE International Conference on Mechatronics and Automation*, pp.1390-1395, 2017.

[21] S. Guo, Y. He, L. Shi, P. Guo, S. Pan, R. Xiao, "Modeling and Experimental Evaluation of an Improved Amphibious Robot with Compact Structure," *Robotics and Computer-Integrated Manufacturing,* vol. 51, pp. 37-52, 2018.

[22] H. Xing, S. Guo, L. Shi, Y. He, S. Su, Z. Chen, and X. Hou, "Hybrid Locomotion Evaluation for a Novel Amphibious Spherical Robot," *Applied Sciences*, vol. 8, no. 2, pp. 156, 2018.

[23] Q. Zhang, and R. Pless, "Extrinsic calibration of a camera and laser range finder (improves camera calibration)," in *Proceeding of IEEE International Conference on Intelligent Robots and Systems*, pp.2301-2306, 2005.

[24] J. Henriques, R. Caseiro, P. Martins and J. Batista, "High-Speed Tracking with Kernelized Correlation Filters," *IEEE Transactions on Pattern Analysis & Machine Intelligence*, vol.37, no.3, pp.583-596, 2015.

[25] L. Bertinetto, J. Valmadre, S. Golodetz, O. Miksik, and P. Torr, "Staple: Complementary Learners for Real-Time Tracking," in *Proceedings of IEEE Conference on Computer Vision and Pattern Recognition (CVPR 2016)*, vol.38, no.2, pp.1401–1409, 2016.

[26] H. Ji, H. Ling, Y. Wu, and C. Bao, "Real time robust L1 tracker using accelerated proximal gradient approach," in *Proceedings of 2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*, vol.157, no.10, pp.1830–1837, 2012.

[27] K. Zhang, L. Zhang and M. Yang, "Fast compressive tracking," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol.36, no.10, pp.2002–2015, 2014.

[28] Q. Liu, X. Zhao and Z. Hou, "Survey of single-target visual tracking methods based on online learning," *IEEE Transactions on Computer Vision*, vol.8, no.5, pp.419–428, 2014.

[29] J. Henriques, R. Caseiro, P. Martins and J Batista, "High-speed tracking with kernelized correlation filters," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, vol.37, no.3, pp.583–596, 2015.