An Autonomous Underwater Vehicle Manipulator System for Underwater Target Capturing

Xinyu Bian
National Key Laboratory of Science and Technology on Underwater Vehicle Harbin Engineering University
Harbin, China
bianxinyu@hrbeu.edu.cn

Tao Jiang
National Key Laboratory of Science and Technology on Underwater Vehicle Harbin Engineering University
Harbin, China
chuanbojiangtao@hrbeu.edu.cn

Teng Guo
National Key Laboratory of Science and Technology on Underwater Vehicle Harbin Engineering University
Harbin, China
2397253574@qq.com

Zhenkun Zhang
National Key Laboratory of Science and Technology on Underwater Vehicle Harbin Engineering University
Harbin, China
zhangzhenkun@hrbeu.edu.cn

Zhaoqun Wang
National Key Laboratory of Science and Technology on Underwater Vehicle Harbin Engineering University
Harbin, China
2305839086@qq.com

Hai Huang*
National Key Laboratory of Science and Technology on Underwater Vehicle Harbin Engineering University
Harbin, China
haihus@163.com

***Abstract*—The operation technology of underwater vehicle manipulator system (UVMS) plays an increasingly important role in the exploration and development of marine resources. However, remotely operated vehicle (ROV) remote control requires skilled operators, which is a challenge for human-machine collaboration. We have designed an autonomous UVMS that greatly reduces dependency on operator during operations and present the overall design scheme of the designed UVMS in this paper. Besides, at the end of this paper, we present the experiment results of the designed UVMS, which show that the designed UVMS can complete autonomous approach and capturing without people's intervention.**

***Keywords*—underwater vehicle manipulator control system, overall design, autonomous underwater operation**

I. Introduction

The 21st century is not only a new epoch of intelligent industrial revolution for the world, but also a new era of large-scale exploitation and utilization of the oceans by mankind [1]-[2]. As the world's most populous country, China needs to meet the requirements of large populations for sea food, health care products, medicines. The collection of sea creatures such as sea cucumbers, scallops and sea urchins raised in offshore marine farms is traditionally done by divers manually. The offshore natural farming environment is not only relatively deep, but also the target organisms are similar to the surrounding water grass, reef and other environments, which increases the human cost and the risk of fishing work. In addition, the inspection and laying of oil and gas pipelines and submarine optical cables, the realization of complex underwater projects, deep-sea rescue and underwater docking and other operations have often exceeded the limits of human body underwater operations. Therefore, it is a major trend to use underwater vehicle to replace divers for artificial operations[3]. So, the research on the autonomous operation technology of underwater vehicle manipulator system (UVMS) can extend the scope of human exploration and development of the ocean and further promote the automatic operation of ocean engineering. Currently, most underwater operations are carried out by remotely operated vehicles (ROVs) equipped with manipulator arms[4], such as SAAB's Seaeye, ECA's ROV, and others. However, such work-class ROVs are relatively expensive and cumbersome. In addition, they need professional operators to operate the vehicle and the manipulator arm at the same time to complete the task[5]. This has greatly raised the threshold for the use of ROV.

*Corresponding Author
Research was supported by National Natural Science Foundation of China through Grant (No. U21A20490, 52025111, 61633009).

Different from ROV operation that relies on manual remote control, autonomous operation of UVMS means that the vehicle relies on its own decision-making in uncertain environment through environmental perception and information processing without manual intervention to complete mission operation tasks independently[6]-[8]. Visual perception can greatly improve the accuracy of information acquisition of UVMS, so as to further improve the operation accuracy and intelligence degree of underwater robots[9]. Therefore, we designed an UVMS with visual perception system, which can complete the underwater operation tasks autonomously, compared with the ROV mentioned above, and verified the feasibility and robustness of the robot system in the pool experiment.

This paper will present an UVMS overall design scheme for underwater target capturing. The rest parts of this paper have been organized as follows. Section II proposes the difficulties and design objective of the designed UVMS. Section III gives a full explanation of UVMS overall design with a proposed control scheme. Pool experiments and results analysis are given in section IV. Conclusions are summarized in section V.

II. Objective

The designed UVMS will traverse from the position dropped by the support ship at a predetermined height, follow the preset path search, or follow the path search planned in real time, and complete the autonomous perception and recognition of the target through visual means during the search process, which is called the cruise mode. If the UVMS finds an operation target in cruise mode, it will approach to the target to a desired position for the following operation through visual guidance. This stage is called target approach mode. Then, based on the control method of hybrid uncalibrated visual servo, the end-effector of the manipulator system is driven to reach the desired pose to complete autonomous operation (capturing). This stage is called operation mode. In the operation mode, the UVMS has two operating states. One is floating operation state, for the situation when UVMS can't sit on the seabed. Another is the bottom-sitting operation state, aiming at the situation when the ocean current has a great influence and the seabed has good situations for UVMS to sitting on. In these three stages, the vision system continues to process the visual images feedback by the lower computer of UVMS and feedback control signals to the UVMS. Through image information continuous processing to judge whether the recognition is

2022 IEEE International Conference on Unmanned Systems (ICUS) | 978-1-6654-8456-5/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICUS55513.2022.9986631

correct, whether the approach is successful, whether the operation is completed. If the operation is complete, UVMS will leave the operation position and enter the cruise mode again. The above procedures indicate that the design of UVMS must consider the following factors:

A. Complex Dynamics Caused by Coupling Effects of Vehicle Body and Manipulator

The coupling effects of the vehicle body and the manipulator is divided into two aspects. On the one hand, when the vehicle body is driving the manipulator, the reaction force and moment of the manipulator will act on the vehicle body and further affect the whole UVMS. On the other hand, the mass and volume of the manipulator relative to the vehicle body cannot be ignored. Therefore, when the manipulator operations, the center of gravity and buoyancy of the whole UVMS will continue changing, resulting in the highly uncertain control dynamics model of the UVMS.

B. Underwater Difficult Perceptual Environment

In natural underwater environments, objects can be obscured and lost from view by currents, plankton and surrounding sediments. Due to the scattering and absorption of light propagating in water, the underwater image will inevitably deteriorate and blur, which will further lead to color distortion and reduce the quality of underwater optical imaging[10]. Moreover, because the refractive index of light in water is higher than that in air, the effective range of optical camera imaging in water is smaller than that in air. Thus, there exists the contradiction of high image quality but small field of vision from close observation, and large field of vision but poor image quality from long distance observation.

C. Complex Underwater Disturbance

Influenced by ocean current and seabed topography together, the ocean disturbance above the UVMS is time-varying in all directions. Therefore, in order to make the UVMS have certain anti-interference operation ability, the UVMS should better have full actuated system. In addition, sensitive position and speed sensors (altimeter, accelerometer, Doppler velocity logger (DVL), etc.) are needed to obtain state's changes of the UVMS. Through observing the state's changes to perceive the disturbance of the environment, the full actuated propulsion system is driven to resist the disturbance of the environment.

III. Overall Design

The detailed description of the UVMS overall design is presented in this section, which takes the requirements into account of underwater target capturing as the primary consideration. The design philosophy is to apply ROV equipped with manipulator arm to achieve the whole functional requirements. The underwater target capturing UVMS are composed of a vehicle body and a 3-DOF electric manipulator (as shown in Fig. 1). The UVMS is 0.84 meters long, 0.75 meters wide and 1.06 meters high, with a total weight of about 95.2 kilograms, among which the manipulator is 15.4 kilograms. The manipulator has three independent joints and one end-effector for capturing. The DH parameters of the manipulator are shown in Tab. I. The total power of the UVMS is 3500 watts.

In order to design the control system, hydrodynamic analysis of UVMS inrush was carried out through computational fluid dynamics (CFD) simulation. In this fluid simulation, STAR-CCM+ software was used to construct a computational domain of 5.5m × 4m × 4m, containing 2.53 million unstructured grids to ensure the quantity and quality of grids as well as the computation time. The entry of the control domain is set as the speed entry and is oriented along the -x axis. The outlet of the control domain is set as the pressure outlet. The left and right planes are symmetric boundaries, and the upper and lower planes are velocity inlets, which can simulate the actual situation of UVMS underwater navigation[11].

TABLE I. DH Parameters of The Manipulator

link	a_i(m)	α_i(deg)	d_i(m)	q_i(rads)
1	0	-90	0.68	q_1
2	0.3	0	0	q_2
3	0.52	0	0	q_3

The layout of underwater target capturing UVMS is shown in Fig. 1, which mainly includes forward-looking sonar, full actuated thruster, visual perception system, navigation and control system and power conversion module, etc. As you can see from Fig. 1, the upper half part of the UVMS is surrounded in buoyancy material, and the high-density subsystem is placed at the bottom to form a large metacentric height, which helps the UVMS to have a large roll recovery moment to resist roll interference. Therefore, an underactuated propulsion system is designed to enable the UVMS to withstand disturbances in all directions of the marine environment. In addition, the UVMS is designed with four legs for UVMS having an ability to sit on the seabed to withstand large environmental disturbances. A certain amount of buoyancy material is attached to the manipulator, to adjust its buoyancy equal to gravity to weaken the changes of the centers of gravity and buoyancy of the entire UVMS when the manipulator operations. Underwater lights are installed at the front of the UVMS for use when the UVMS operate in poor lighting conditions.

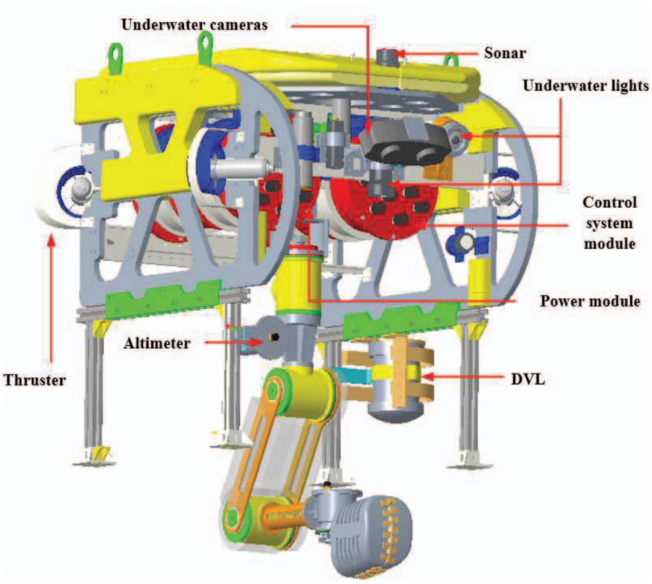

Fig. 1. The layout of underwater target capture UVMS.

As shown in Fig. 2 and Fig. 3, the hydrodynamic analysis of UVMS surging was carried out by CFD simulations to further decrease the water resistance. In addition, the pose of the manipulator relative to the body is constantly changing during the simultaneous coordinated movement to complete the grasping operation. Therefore, the surging resistance of

UVMS in different manipulator pose has simulated[12]. Tab. II shows the UVMS surging resistance at different speeds and manipulator poses. Moreover, the hydrodynamic analysis of UVMS swaying was also conducted through CFD simulations as shown in Figs. 4 and 5. Tab. III shows the UVMS swaying resistance at different speeds and manipulator poses.

TABLE II. RESISTANCE UNDER DIFFERENT SURGING SPEED WITH VARIOUS POSES

Velocity (m/s)	Resistance (N)				
	Pose 1	*Pose 2*	*Pose 3*	*Pose 4*	*Pose 5*
0.25	12.4	13.2	12.5	12.4	12.4
0.50	49.7	52.8	50.0	49.7	49.6
0.75	111.9	118.8	112.6	111.9	111.7
1.00	198.8	211.2	200.1	198.9	198.5
1.25	310.7	329.9	312.7	310.9	310.2

TABLE III. RESISTANCE UNDER DIFFERENT SWAYING SPEED WITH VARIOUS POSES

Velocity (m/s)	Resistance (N)				
	Pose 1	*Pose 2*	*Pose 3*	*Pose 4*	*Pose 5*
0.3	25.7	27.0	26.8	26.9	25.4
0.6	100.2	104.8	104.7	105.1	104.1
0.9	224.0	233.7	233.9	235.8	231.9
1.2	395.9	415.4	415.5	419.8	414.2

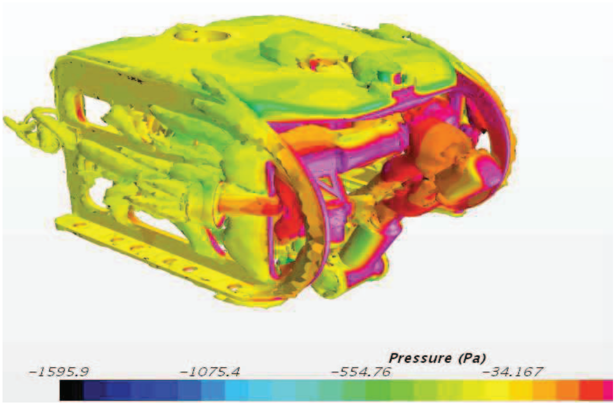

Fig. 2. The vorticity distribution of the UVMS surging.

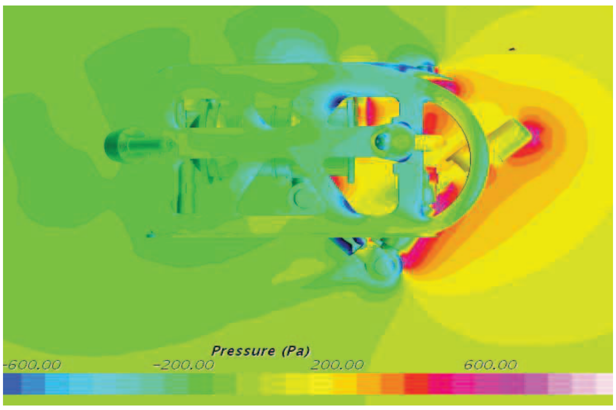

Fig. 3. The pressure distribution of the UVMS surging.

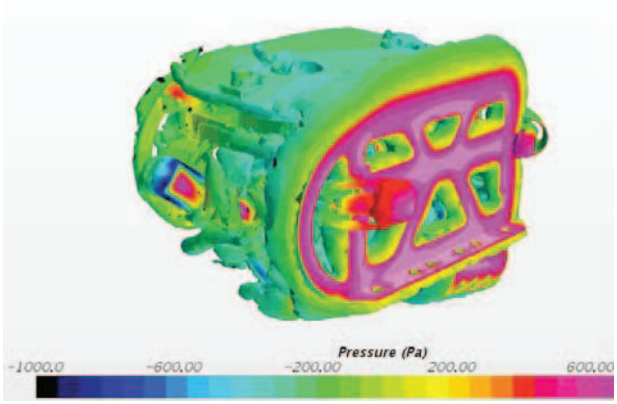

Fig. 4. The vorticity distribution of the UVMS swaying.

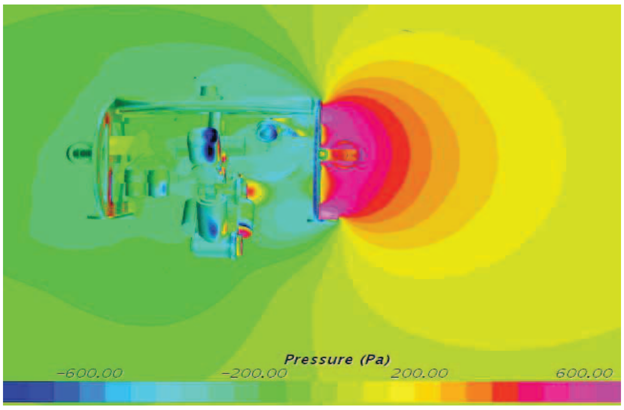

Fig. 5. The pressure distribution of the UVMS swaying.

The hardware control system of underwater target capturing UVMS can be divided into the upper computer control system with the surface industrial computer as the core and the lower computer control system with the PC104 in the cabin as the core, and they communicate with each other in the form of network through optical fiber. The upper computer control system is mainly responsible for the upper abstract tasks such as motion planning algorithm solution, hand-eye coordination grasping algorithm solution and real-time image processing. The lower computer control system is mainly responsible for signal acquisition of UVMS sensors, direct drive of actuators (thrusters, manipulator motors), electromagnetic relay control and other underlying tasks. The two control systems are connected by neutral buoyancy optoelectronic composite cable and are powered by 220V AC on the support ship. The hardware control system architecture of underwater target capturing UVMS is shown in Fig. 6.

The upper computer control system is based on two surface industrial computers. The control interface of the UVMS is written based on MPC in Visual C++, through which switches of each component of the UVMS can be controlled, and the real-time status of the UVMS can be monitored (including the attitude and position of the vehicle body, and the position of each joint of the manipulator, etc.), which is convenient for algorithm debugging. In addition, the motion planning algorithm of UVMS, hand-boat coordination algorithm and hand-eye coordination grasping algorithm are integrated in Visual C++, and can be directly called through the interface. Another industrial computer based on Ubuntu performs real-time processing tasks of UVMS images. Switches and optical transceivers connect two industrial computers to the lower computer using optical fiber as the medium.

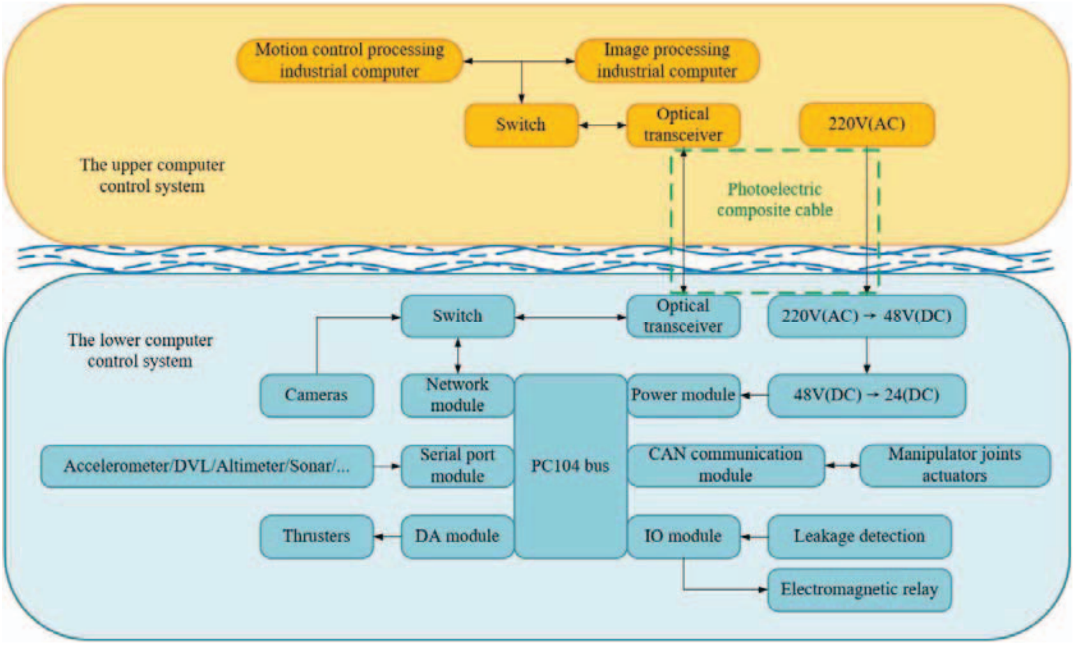

Fig. 6. Hardware architecture of the UVMS.

The lower computer control system takes PC104 bus as the core, and converts 220V AC to 48V DC through a power module. The signals acquisition of altimeter, Doppler velocimeter, accelerometer, sonar and other sensors are realized through the serial port modules of PC104. The lower computer realizes the communication between PC104 and manipulator joints driver through CAN communication module, and then realizes the control of manipulator joints. The lower computer converts digital signals into analog signals through DA conversion module to drive each thruster and adjust the brightness of underwater lights. In addition, it directly controls the on-off of each electromagnetic relay through the output part of IO module, and collects water leakage sensor information through its input part. Through the input of 24V DC to the power module to drive the PC104 modules work. The models and functions of each sensor are shown in Table IV.

TABLE IV. SENSORS OF THE UVMS

Sensors	**Model**	**Function**	**Communication mode**
Altimeter	Tritech-PA 500	Measure the distance between the UVMS and the seabed	RS-232
DVL	NavQuest 600	Measure the horizontal movement speed of the UVMS	RS-232
Accelerometer	Accelnet-MTi 300	Measure the attitude angle and triaxial acceleration of the UVMS	RS-232
Sonar	Tritech Micron Sonar	Detect obstacles in front of the UVMS	RS-232
Underwater camera	Self-developed	Use vision to perceive the environment and the target	Network

TABLE V. ACTUATORS OF THE UVMS

Actuators	**Model**	**Operating voltage**	**Communication mode**
Thruster	Haoye T300/T280	48V	DA
Manipulator motor	Yggt HRB01	48V	CAN 2.0
End-effector steering gear	ROBOTIS W270	12V	RS-485

The actuator system of the UVMS consists of six thrusters and a 3-DOF manipulator. The UVMS are equipped with six thrusters, including four thrusters vector arranged in the horizontal plane to regulate the surging, yawing and swaying motions of the UVMS, and two thrusters in the vertical plane to regulate the heaving and pitch motions of the UVMS. The peak thrust of the thrusters arranged by the four vectors is about 83N forward and 51N backward, and the maximum thrust of the two vertical thrusts is basically the same, about 73N forward and backward. The power of each thruster is about 500 watts. The torque motor, reducer, absolute encoder and servo driver of the electric manipulator are integrated in the manipulator joints, reducing the volume occupation in the cabin. The peak torque of a single motor is 0.9N·m, and the reduction ratio is 1:150. The end-effector is driven by the steering gear with a peak torque of about 10N·m and a power of about 50 watts. Steering gear adopts position control based on current feedback to ensure grasping efficiency. The motor and steering gear of manipulator can feedback its absolute position by sensor. The actuator system details of the UVMS configuration are shown in Table V.

The motion control algorithm for UVMS autonomous approach and capturing operations is shown in Fig. 7. After measuring the pose of the target by binocular camera, the pose of the target will be given first. According to the current pose of the end-effector in the workspace, the desired pose and desired velocity $[\eta_{eed}, \dot{\eta}_{eed}]_t$ of the workspace at each time point T within the preset time t are solved based on the quintic polynomial, and then a desired trajectory is formed in the workspace to generate the trajectory error in the geodetic coordinate system for carrying out the control. After the Sigmoid function having been applied to the trajectory tracking errors in the workspace, the feedback terms of the controller will be formed by the hydrodynamics model of the UVMS. In addition, feedforward compensation is estimated by disturbance observer according to the real-time status of UVMS impacted by the internal disturbance, external disturbance and the model uncertainty. The model controller based on sigmoid function considers the influence of restoring force (moment) and other dynamic changes on the system, so it can realize more accurate control and faster response.

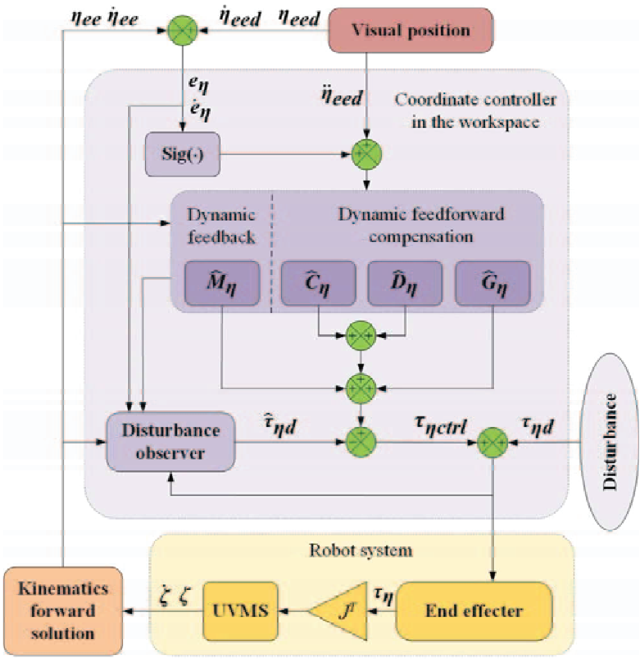

Fig. 7. Block diagram for the work space coordinated controller.

IV. Experiments and Results

This section mainly carries out experimental verification. The experimental process is divided into two parts: underwater target autonomous approach experiment and underwater autonomous capturing experiment.

A. Underwater Target Autonomous Approach Experiment

Fig. 8 shows the process of UVMS gradually approaching the target autonomously under position based visual servoing control from the perspective of underwater camera. Fig. 9 shows the position change curve of the target in the vehicle body coordinate system during the approach process of the underwater target. Combining Fig. 8 and Fig. 9, it can be seen that UVMS approaches the target by simultaneously swinging and surging which is driven by vector arrangement drive system while UVMS was diving, after the UVMS having found the target. The results show that by applying the control scheme mentioned above, the UVMS has achieved the autonomous target approach task.

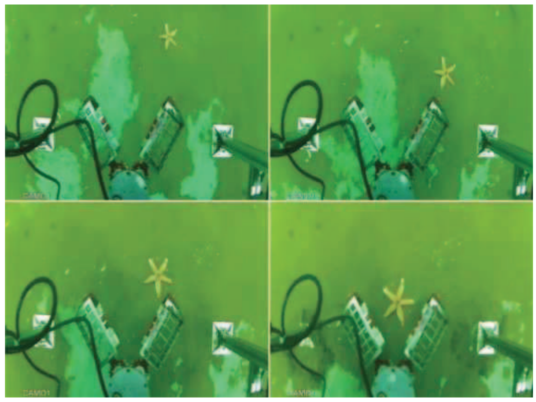

Fig. 8. Autonomous target approach of UVMS from the perspective of underwater camera.

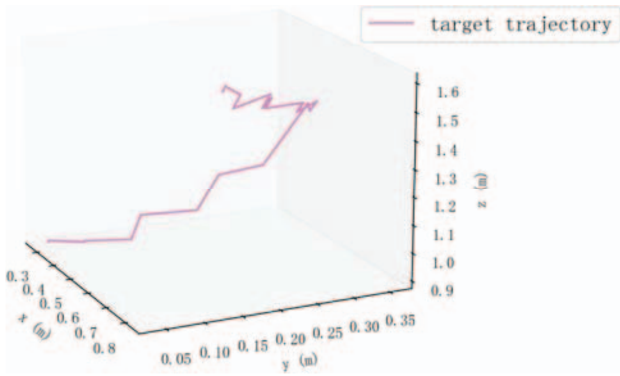

Fig. 9. Position change curve of the target in the vehicle body coordinate system.

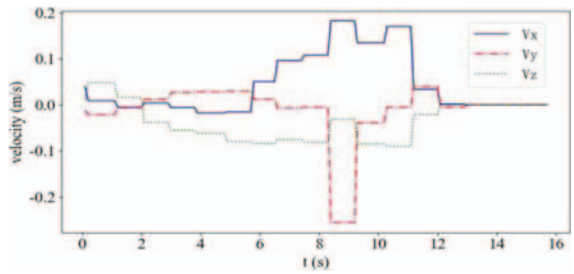

Fig. 10. Vehicle speed change curves.

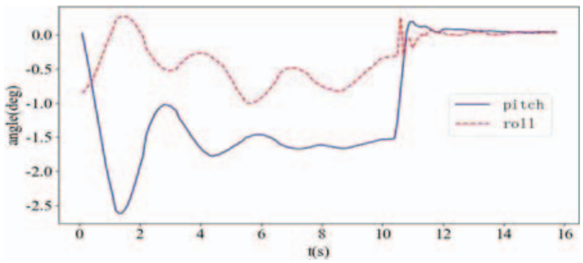

Fig. 11. Curves of vehicle pitch and roll angle changes.

B. Underwater Autonomous Capturing Experiment

Fig. 12 shows the motion curve of the end-effector during capturing. Fig. 13 shows the motion of three-joint manipulator underwater target capturing from the perspective of underwater camera. The Euclidean distance curve between the target and the end-effector of the manipulator is shown in Fig. 14. In the process of capturing, angle change curves of basal joint, elbow joint and wrist joint are shown in Fig. 15, Fig. 16 and Fig. 17 respectively. Figs. 12 to 17 show that by gradually adjusting the three joint angles of the manipulator, the end-effector finally move to the target position, which illustrate that the UVMS can successfully autonomous complete the capturing task.

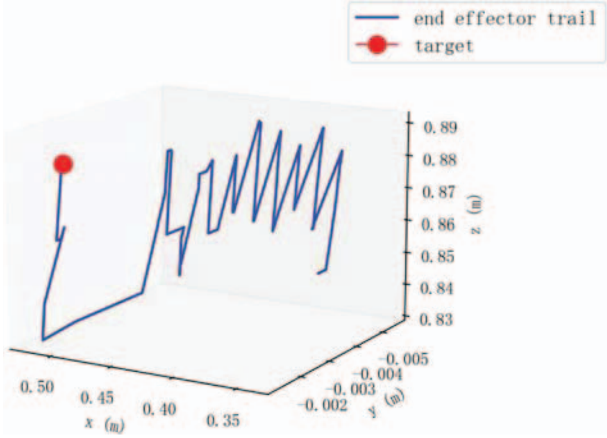

Fig. 12. Trajectory of end effector during underwater capturing.

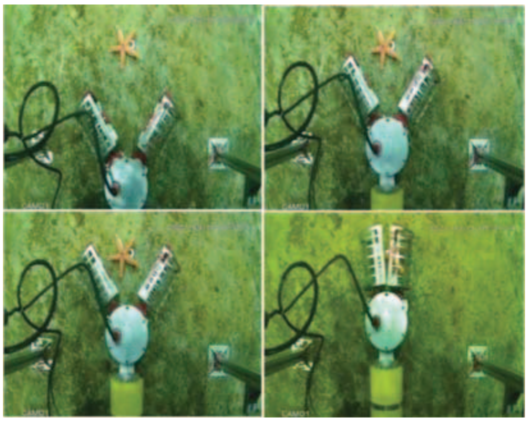

Fig. 13. Autonomous target capturing of UVMS from the perspective of underwater camera.

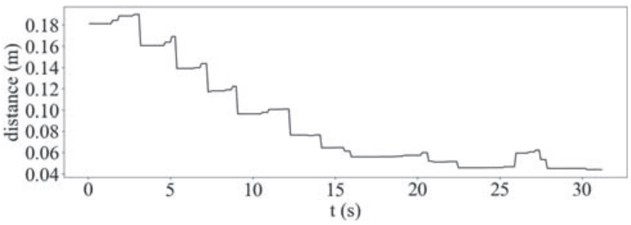

Fig. 14. Distance change between end actuator and target.

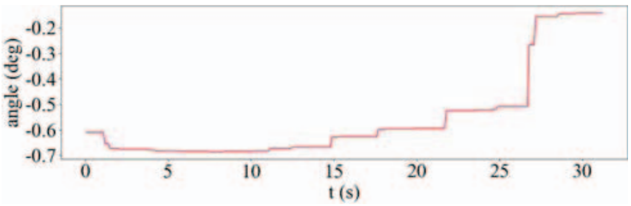

Fig. 15. Angle change curve of base joint.

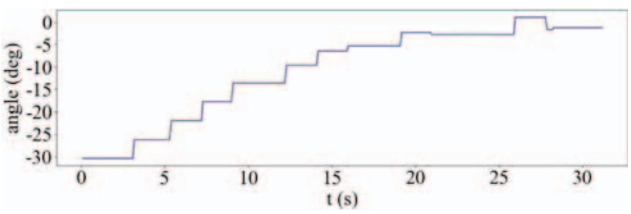

Fig. 16. Angle change curve of elbow joint.

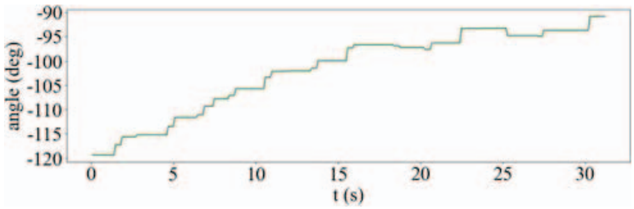

Fig. 17. Angle change curve of wrist joint.

V. Conclusion

In order to realize underwater autonomous approach and autonomous grasping, a UVMS design scheme is proposed in this paper. Moreover, based on the designed UVMS, we have proposed a vision-based control method to complete the autonomous operation control of UVMS. In the pool experiments, the UVMS we designed successfully completed the autonomous approach and capture operation, which verified the UVMS scheme and the vision-based autonomous control method. Based on this, the UVMS also may replace humans for other underwater tasks by replacing its end-effector. We will further study the anti-interference operation control of the UVMS by artificial intelligence technology to improve the precision operation ability and robustness of the UVMS end-effector.

References

[1] H. Xiao, R. Cui and D. Xu, "A Sampling-Based Bayesian Approach for Cooperative Multiagent Online Search With Resource Constraints," in IEEE Transactions on Cybernetics, vol. 48, no. 6, pp. 1773-1785, June 2018, doi: 10.1109/TCYB.2017.2715228.

[2] Geoff Krause, Trip Report for the November 2014 Marketing Mission to China, (2014) http://www.pscha.org.

[3] Loris Barbieri, Fabio Bruno, Alessandro Gallo, Maurizio Muzzupappa, Maria Laura Russo, “Design, prototyping and testing of a modular small-sized underwater robotic arm controlled through a Master-Slave approach,” Ocean Engineering, vol. 158, pp. 253-262, 2018.

[4] Z. Hu, L. Wang, C. Ye and Z. He, "Research of acoustic survey devices applied on deepsea vehicles," 2016 IEEE/OES China Ocean Acoustics (COA), 2016, pp. 1-5, doi: 10.1109/COA.2016.7535702.

[5] M. Prats, J. C. Garcia, J. J. Fernandez, R. Marin and P. J. Sanz, "Advances in the specification and execution of underwater autonomous manipulation tasks," OCEANS 2011 IEEE - Spain, 2011, pp. 1-5, doi: 10.1109/Oceans-Spain.2011.6003619.

[6] Prats M, Ribas D, Palomeras N, et al., “Reconfigurable AUV for intervention missions: a case study on underwater object recovery,” Intelligent Service Robotics, vol. 5, pp. 19-31, 2012.

[7] Bin Xu, Shunmugham R. Pandian, Norimitsu Sakagami, Fred Petry, “Neuro-fuzzy control of underwater vehicle-manipulator systems,” Journal of the Franklin Institute, vol. 349, pp. 1125-1138, 2012.

[8] Santhakumar Mohan, Jinwhan Kim, “Indirect adaptive control of an autonomous underwater vehicle-manipulator system for underwater manipulation tasks,” Ocean Engineering, vol. 54, pp. 233-243, 2012.

[9] Enrio Simetti, Giuseppe Casalino, Sandro Torelli, Alessandro Sperinde and Alessio Turetta, “Floating Underwater Manipulation: Developed Control Methodology and Experimental Validation within the TRIDENT Project,” Journal of Field Robotics, vol. 31, pp. 364-385, 2014.

[10] L. Hong, X. Wang, Z. Xiao, G. Zhang and J. Liu, "WSUIE: Weakly Supervised Underwater Image Enhancement for Improved Visual Perception," in IEEE Robotics and Automation Letters, vol. 6, no. 4, pp. 8237-8244, Oct. 2021, doi: 10.1109/LRA.2021.3105144.

[11] Savitsky D., “Hydrodynamic design of planing hulls,” Marine Technology, vol.1, pp. 71-95, 1964.

[12] He Zhang, Yuru Xu, Haopeng Cai, “Using CFD Software to Calculate Hydrodynamic Coefficients,” Journal of marine science and technology, vol. 9, pp:149-155, 2010.