Modular Design and Control of an Underwater Biomimetic Vehicle-Manipulator System

Rui Wang, Shuo Wang, Yu Wang and Chong Tang

***Abstract*—This paper addresses the modular design of an underwater biomimetic vehicle-manipulator systems (UBVMS) propelled by undulatory fins. Motivated by the cuttlefish, which can perform flexible motions by undulatory propulsion in narrow spaces, our UBVMS with two undulatory fins is designed. The specific implementation of mechanical structure is detailed. In particular, the design philosophy of modularity is incorporated into the design of the UBVMS, which provides versatility for the UBVMS and facilitates maintenance and future development of the UBVMS, as new modules can be added to replace the obsolete modules easily. In the end, experimental results demonstrate the feasibility and effectiveness of the mechanism and the control system.**

I. Introduction

Underwater vehicle-manipulator systems (UVMS) are widely used in the fields of ocean development, marine environmental protection, underwater operation, military reconnaissance, and so forth [1], [2]. Generally, UVMS is composed of two parts, including the underwater vehicle and the manipulator, which can be designed, manufactured, and then assembled together, respectively.

Recently, biomimetic underwater vehicles (BUV) propelled by undulatory fins have received much attention, whose appealing features involves stronger disturbance rejection, more remarkable maneuverability, and quieter actuation than conventional underwater vehicles equipped with thrusters [3]. Therefore, underwater biomimetic vehicle-manipulator systems (UBVMS) are designed by integrating the propulsion mode of undulatory fins with the UVMS, which is a beneficial attempt to solve the challenging problems of hovering control and disturbance rejection control of UVMS.

For more than ten years, researchers have developed several kinds of BUVs propelled by undulatory fins, such as Heriot-Watt University [4], Northwestern University [5], [6], Nanyang Technological University [7], Osaka University [8] et al. However, as far as we know, most of researchers focus on undulatory fin control, but seldom consider vehicle modularity for those BUVs, which is of primary importance for developments of application specific robot solutions quickly and cost effectively.

This paper presents an novel modular UBVMS with biomimetic propulsion. Specifically, the UBVMS is composed of three modules, including the main body, the underwater manipulator and the biologically inspired propulsor. Each module can be individually removable and reassembled. The concept design provides versatility for the underwater robot system and also facilitates in the maintenance and future development of the UBVMS, as new modules can be added to replace the existing modules easily. Moreover, by reconfiguring the modules of UBVMS, other version of UVMS with undulatory propulsion is developed. In the remainder of this paper, the modules details of the UBVMS are described in Section II. Sections III introduces the control system configuration of the UBVMS. Experimental results are further provided in section IV. Finally, the conclusion are presented in Section V.

II. Modules Details

Cuttlefish are marine animals swimming by undulations of a pair of lateral fins. They can perform flexible motions in narrow spaces with water turbulence. Inspired by this unique propulsion mode, our UVMS propelled by undulatory fins is designed. Specially, the mechanism design for the UBVMS is based on modular concepts. Specially, each module is a mechatronic system with interfaces of mechanics, power and communication. As shown in Fig. 1 and Fig. 2, the UBVMS is composed of three modules, i.e., main body, underwater manipulator, and biologically inspired propulsor. Each module is connected by screws, iron hoops, bearings or other mechanical parts and interacts with each other via the various communication interfaces. Notice that the propulsor has independent power module, such that it needs not be connected to an external power interface. Detail descriptions about each module are presented in the later section.

A. Main Body

The main body of the UBVMS is a waterproof underwater platform used to place the visual system, controller, and power module, etc. Fig. 3 shows the mechanical design of the main body. Vision system is installed in front of the main body. The controller and an inertial navigation system (INS) are placed in the central section. In addition, the power module is $24V$ lithium battery packs, which provide power for electronic devices and servo motors. Moreover, the pitch angle of the UBVMS can be controlled by adjusting the position of the

This work was supported in part by the National Natural Science Foundation of China under Grant 61233014, 51175496 in part by the Foundation for Innovative Research Groups of the National Natural Science Foundation of China under Grant 61421004, and in part by the Beijing Natural Science Foundation under Grant 3141002.

R. Wang, Y. Wang, and C. Tang are with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China, and also with University of Chinese Academy of Sciences, Beijing 100049, China.

S. Wang is with the State Key Laboratory of Management and Control for Complex Systems, Institute of Automation, Chinese Academy of Sciences, Beijing 100190, China (corresponding author: Prof. S. Wang, shuo.wang@ia.ac.cn)

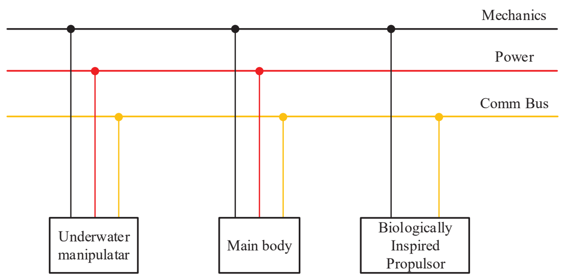

Fig. 1. Sketch map of the modular design.

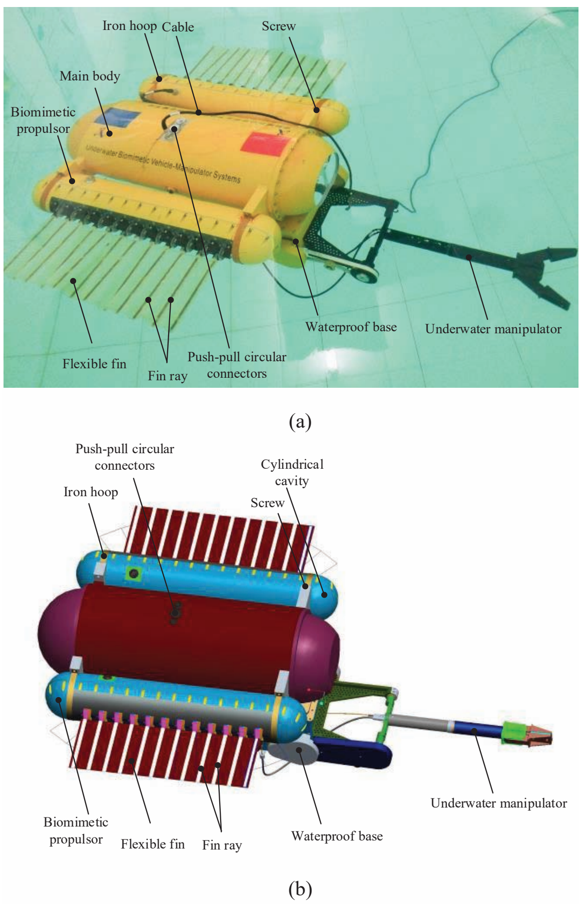

Fig. 2. Schematic drawing of the UBVMS. (a) Prototype. (b) Mechanical design

counterweight. Notice that the UBVMS presented in this paper is a tethered mobile underwater robot. A waterproof cable is used to connect the controller inside the main body to the remote console by push-pull circular connectors.

B. Underwater Manipulator

As shown in Fig. 4, the underwater manipulator is composed of a waterproof base, a 3 degrees of freedom (DoF) multi-link structure, waist joint and gripper. Additionally, the waist joint can be installed in the interior of the main body to rotate the waterproof base. The other four servo motors and their motor drivers are placed inside the waterproof base. In particular, those servo motors are connected to the joints

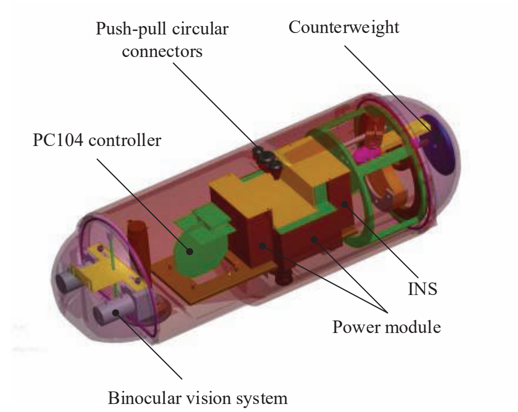

Fig. 3. Mechanical design of the main body.

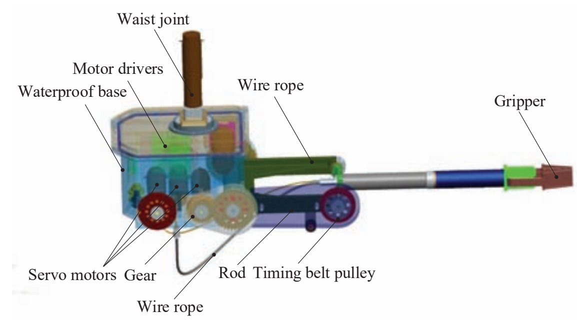

Fig. 4. Mechanical design of the manipulator module.

of the manipulator by timing belt pulley, gear or wire rope transmission. The multi-link structure is constituted by two rods and the gripper with small volume and light weight. The base weight in air is $11.04kg$, while the mass of the multi-link structure is $0.889kg$. Thus the barycenter of the underwater manipulator is located in the waterproof base. As the base unit is mounted on the vehicle, this novel structure greatly lowers the coupling between the manipulator and the vehicle, which are conductive to high-speed underwater operations and coordinative controls between the manipulator and the vehicle [9].

C. Biologically Inspired Propulsor

Fig. 5 shows the mechanical design of the propulsor, which consists of two sub-modules: cylindrical cavity and long fin. Specifically, the cylindrical cavity is mainly made of aluminum alloy, which reduces the weight of the propulsor while maintains sufficient strength. Moreover, the mechanism design of the cavity reduces the motion resistance in the underwater space. Driving board, batteries and servo motors for driving the long fin are integrated inside the cylindrical cavity. The long fin consists of twelve fin rays which are connected to one another by a flexible membrane made of thin rubber isometrically. Each fin ray can be independently controlled by the corresponding servo motor. In particular, owing to the modular design, the propulsor module can swim in the water independently or be used to construct various

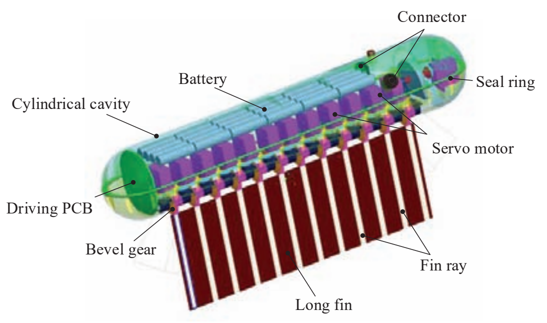

Fig. 5. Mechanical design of the propulsor module.

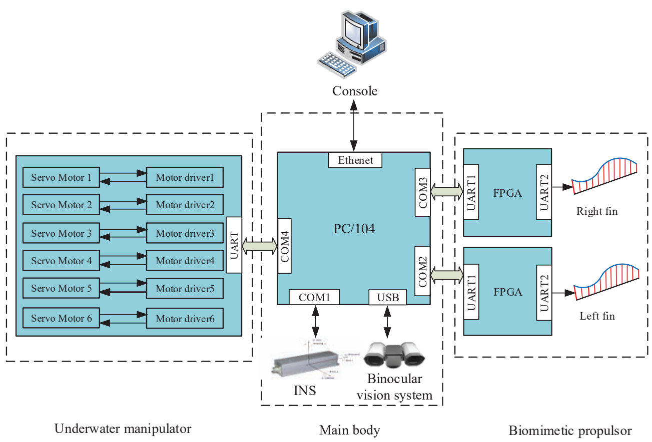

Fig. 6. Control system configuration of the UBVMS.

biomimetic underwater robots with oscillating fin propulsion [10].

III. Control system configuration

In this section, the system configuration of the main body, the manipulator, and the propulsor of the UBVMS are introduced as shown in Fig. 6, respectively. It should be mentioned that each module is connected with each other through a standard serial port or Ethernet port, which facilitates the maintenance and update of the module software.

In the main body, a PC/104 module (Advantech 3363D) is employed as the master chip mainly to achieve the motion control of the UBVMS, the digital image process, and the autonomous operation control of the underwater manipulator et al. Moreover, an INS to calculate the position, orientation, and velocity of the UBVMS and a binocular vision system for target identification and location are connected to the PC/104 controller through a serial port and an USB interface, respectively. Moreover, since the PC/104 controller is connected to remote console via a cable, the console is able to control the UBVMS manually.

As for the underwater manipulator, the drive of servo motor 1 is connected to the PC/104 through the serial port. The rest of motor drives are linked to each other using the CAN bus. Two closed loops of the motor including velocity loop and position loop are applied to realize the control of DC servo motor. Thus high-speed and high-precision controls of the joint positions of the underwater manipulator can be achieved.

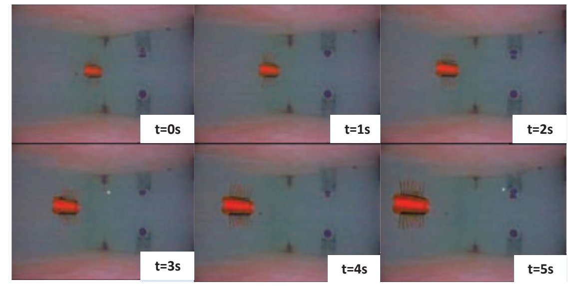

Fig. 7. Snapshots of the swimming test of the biologically inspired propulsor.

The system configuration for the propulsor is based on embedded control system. A field programmable gate arrays (FPGAs) chips (ALTERA EP3C55F484) is used as driving unit to control the undulatory fin. Specially, the driving unit is in charge of receiving the commands from the PC/104 module, parsing out motion parameters, i.e. frequency, amplitude, phase difference, deflection angle, and propagating direction of the waves on long fins, and finally sending corresponding commands to servo motors under the specific communication protocol.

With the coordinated control of the propagating waves on fins, the long fin can perform various undulating or flapping motion and further create vector forces in 3-D. Furthermore, the UBVMS can perform diversified locomotion patterns, including forward/backward swimming, diving/floating motion, and turning maneuver with high mobility.

IV. Experiments

In order to illustrate the feasibility of the mechanism and the control system of the UBVMS, Four experiments, including the swimming test of the propulsor, the free-floating autonomous manipulation, the multimodal swimming test of the UBVMS, and the depth control experiment are conducted. All the experiments are performed in an indoor pool with dimensions of 5 m $\times$ 4 m $\times$ 1.1 m (length $\times$ width $\times$ depth).

Consecutive snapshots of the swimming test of the biologically inspired propulsor are given in Fig. 7. Fig. 8 plots a comparison of time-averaged forward velocity with different frequencies and amplitudes. It is observed that the propulsor can swim in the water independently and the long fins can generate sine wave with different parameters configurations. The experimental results demonstrate the performance of the mechanical design and the control system of the biologically inspired propulsor.

In the free-floating autonomous manipulation, we just conduct autonomous manipulation, but not consider the motion of the UVMS. In particular, a red target tied by a rope is placed in the view of binocular system. Fig. 9 gives the image sequence of the autonomous manipulation. The experimental result validates the effectiveness of the mechanical structure of the underwater manipulator.

The third experiment is the multimodal swimming test of the UBVMS. The experiment results are shown in Fig. 10,

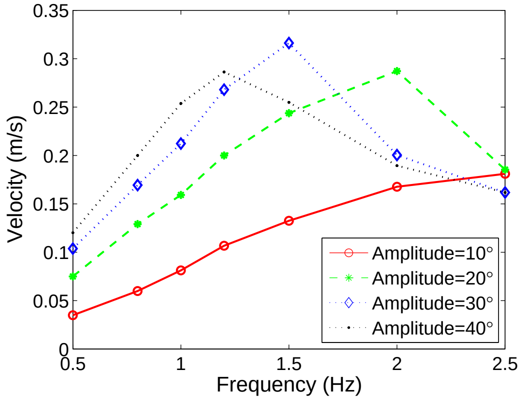

Fig. 8. Swimming velocity evaluation by modulating the oscillation frequency and/or amplitude.

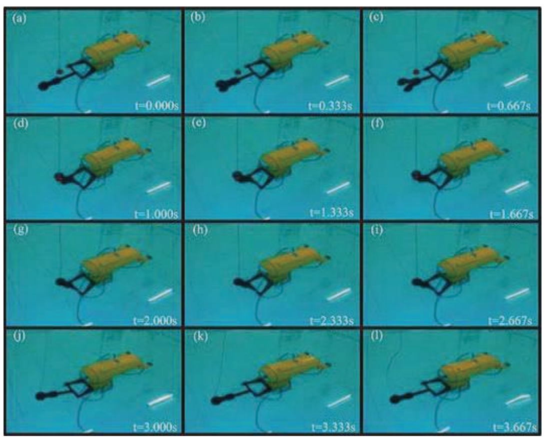

Fig. 9. Snapshots of the free-floating autonomous manipulation.

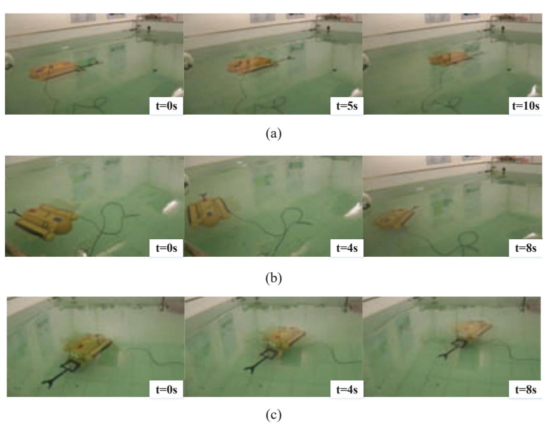

Fig. 10. Snapshots of the multimodal swimming test of the UBVMS.

where Fig. 10(a) shows the forward swimming of the UBVMS, turning maneuver is presented in Fig. 10(b), Fig. 10(c) depicts the results of backward swimming. It can be seen that the modular design of the UBVMS is rational and effective.

In the depth control experiment, the initial depth of the UBVMS is 0.2 m and the desired depth is 0.7 m. Fig. 11 shows the snapshots of depth control experiment. The experimental results indicate the UBVMS can maintain at a fixed depth under the depth controller. Moreover, the experiment verifies the feasibility of implementing complex motion control algorithms on the UBVMS.

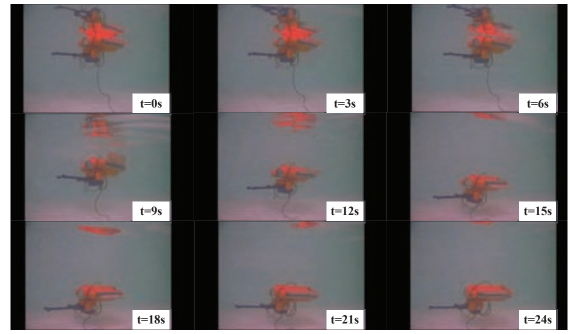

Fig. 11. Snapshots of the depth control experiment.

V. Conclusion

A modular UBVMS with undulatory fin propulsion has been introduced. Preliminary details of the modules and the control system configuration have been given. Four experiments, including the swimming test of the biologically inspired propulsor, the free floating autonomous manipulation, the multimodal swimming test of the UBVMS, and the depth control experiment are conducted. The experimental results validate the performance of the UBVMS. The proposed modular design method for the UBVMS should be a beneficial attempt, and it needs further research in future.

References

[1] Y. Cui and J. Yuh, "A unified adaptive force control of underwater vehicle-manipulator systems (UVMS)," in *Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Las Vegas, Nevada, October 2003, pp. 553-558.

[2] G. El-Ghazaly, M. Gouttefarde, and V. Creuze, "Hybrid cable-thruster actuated underwater vehicle-manipulator systems: A study on force capabilities," in *Proceedings of the 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Hamburg, Germany, September 2015, pp. 1672-1678.

[3] J. Yu, M. Wang, M. Tan, and J. Zhang, "Three-dimensional swimming," *IEEE Robotics & Automation Magazine*, vol. 18, no. 4, pp. 47-58, 2011.

[4] M. Sfakiotakis, D. Lane, and B. Davies, "An experimental undulating-fin device using the parallel bellows actuator," in *Proceedings of the 2001 International Conference on Robotics and Automation*, Seoul, South Korea, May 2001, pp. 2356-2362.

[5] O. Curet, N. Patankar, G. Lauder, and M. MacIver, "Mechanical properties of a bio-inspired robotic knifefish with an undulatory propulsor," *Bioinspiration & Biomimetics*, vol. 6, no. 2, pp. 026004, 2011.

[6] R. Torres, O. Curet, G. Lauder, and M. Maclver, "Kinematics of the ribbon fin in hovering and swimming of the electric ghost knifefish," *Journal of Experimental Biology*, vol. 216, no. 5, pp. 823-834, 2013.

[7] C. Zhou and K. Low, "Design and locomotion control of a biomimetic underwater vehicle with fin propulsion," *IEEE/ASME Transactions on Mechatronics*, vol. 17, no. 1, pp. 25-35, 2012.

[8] M. Rahman, S. Sugimori, H. Miki, R. Yamamoto, Y. Sanada, and Y. Toda, "Braking performance of a biomimetic squid-like underwater robot," *Journal of Bionic Engineering*, vol. 10, no. 3, pp. 265-273, 2013.

[9] Y. Wang, S. Wang, Q. Wei, M. Tan, C. Zhou, and J. Yu, "Development of an underwater manipulator and its free-floating autonomous operation," *IEEE Transactions on Mechanicals*, vol. 21, no. 2, pp. 815-824, 2016.

[10] R. Wang and S. Wang, "Design and implementation of a biomimetic underwater propeller with a undulating long fin," *Journal of Huazhong University of Science and Technology (Nature Science Edition)*, vol. 43, no. s1, pp. 408-411, 2015.