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Study on Cooperative Control Algorithm of Two Spherical Amphibious Robots

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***Abstract* - Amphibious spherical robot moving in a confined space or turbid water must have an effective motion control device and optimized algorithms. This paper proposed a control strategy for two amphibious robots in order to maintain a long time-parameterized path when the robot is moving underwater. Inspired by the biological phenomenon, this paper designs an artificial cooperative mode for two amphibious robots. The control method is based on underwater environment and we also take a detailed mechanical analysis of the thrust device, so the direction of the robot can be adjusted in real time according to the stability module, the purpose of cooperation between the two robots can be achieved. At the end of the paper, the underwater experiment is performed to analyze the cooperation and control system in order to give the best solution for cooperation and motion control methods of two robots.**

Index Terms – Biological Inspiration, Amphibious Spherical Robot, Underwater Robot, Multifunction Robot, Underwater Cooperation

I. INTRODUCTION

In recent years, there has been a growing interest in using large numbers of amphibious spherical underwater robot to realize cooperative control [1]. This study has mainly focused on dynamic performance, locomotion control, swimming efficiency. such swarm offer potentials to increase sensor density, within the same or cost-effective system and provide excellent adaptability and flexibility in task execution [2]-[3].

In our previous research, our team designed an artificially robot consisting of eight rotating steering motors to enable the robot to walk on land and underwater[4]-[6]. However, such design methods have many limitations. For example, the stability of the movement is insufficient, and the speed is not meet requirement. The most important thing is that this designation does not have communication and stability control system, so that the robots cannot communicate with each other, thereby it is difficult to implement complex motion modes and performing complex detection tasks.

To overcome the limitation of previous design amphibious spherical robots, this paper proposed a new type amphibious robot with collaborate module, the algorithm of the cooperation of two robots is also designed and the algorithm is analyzed in detail. According to the parameters in the real-time monitoring and control algorithm of the stability control system, the communication sensor installed on the surface is used to receive data between of the two robots, as shown in Fig. 1.

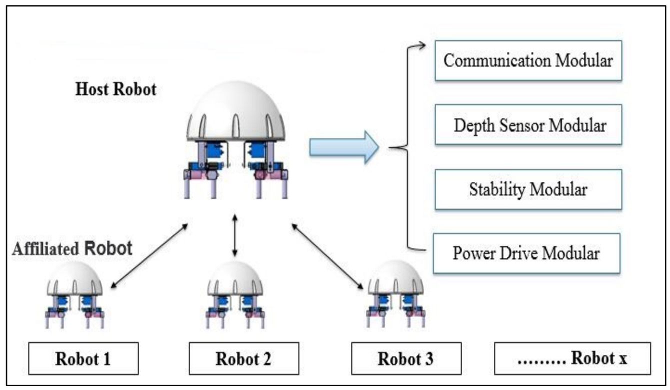


Fig. 1. Diagram of the spherical amphibious robot

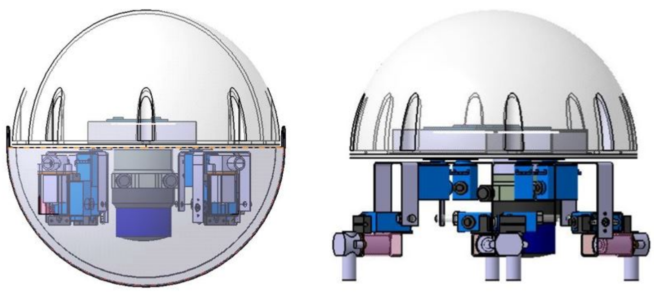
The rest of this paper is organized as follows: Discussion of the overall structure and control system, which covers our amphibious spherical robot is presented in Section 2. The stability control method and the control motion of underwater robot is analyzed. in Section 3. Conducted two collaborative experiments containing two different robots in Section 4. Section 5 presents the conclusion and suggestions for next generation relevant research.

II.STRUCTURE AND ELECTRONIC MODELING

A. The structure of the novel robot

In order to improve the stability and flexibility of the amphibious spherical robot, the external structure was also redesigned. Compared with the previous designation, this robot added a communication module and stability control device, so that the two robots can perform movement in real time [7]-[9]. Relay on communication module, which lays the foundation for collaboration functions [10]. The mechanical structure is shown in Fig. 2 below:

The overall design of the robot is spherical, mainly because the sphere can achieve a better degree of freedom when



(a) Underwater mode **(b) Land mode**

Fig. 2. Movement modes of the spherical amphibious robot

moving under water and the robot can be drived to any position. This robot is composed of the upper and lower hemispheres. The upper hemisphere is mainly for the assembly of electronic control systems, and the lower hemisphere is mainly equipped with walking devices and communication modules. The communication module is a sonar [11]- [13], which must be installed outside the robot so that it can be in full contact with water, so the communication module is mounted on the bottom of the intermediate board.

B. Electronic design

Because the robot can only install the control system in the upper hemisphere, due to space constraints, the control system needs to be simplified as much as possible without affecting the function of the control system [14], as shown in Fig. 3. The main controller uses the ardunio because the ardunio can fully realize the data acquisition of the sensor and motor control, that often used in robot control devices [15]-[17]. The communication system and the main controller are connected by RS232 interface to realize data transmission and reception [18]. The schematic diagram is shown in Fig. 4.

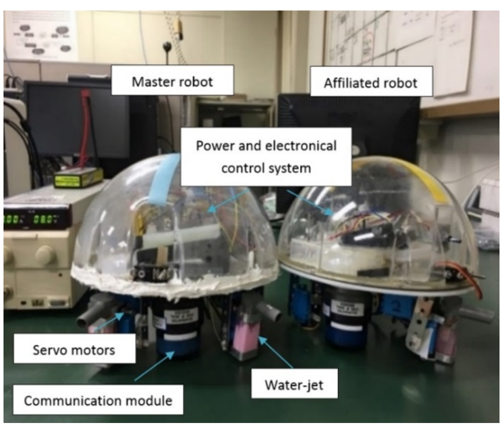


Fig. 3. Hardware layout of the amphibious spherical robot

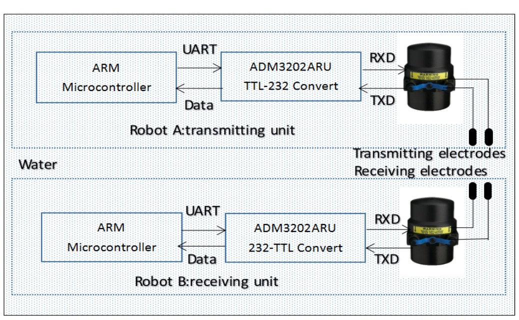
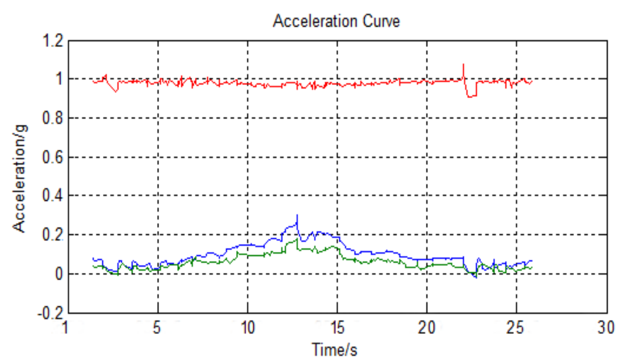


Fig. 4. Control modeling of the communication device

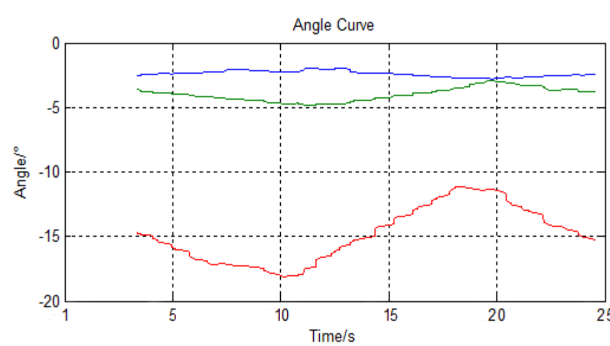
III. Analysis of Underwater Motion Control

The previous discussion refers to the trajectory tracking problem. However, the multi-robot formation control is in fact reduce to the tracking problem when the master robot cooperated with the follower robot, which constitute the virtual formation [19]-[21]. So, we proposed a method for mutual positioning of two robots based on communication device and a stabilization module and use the different delay characteristics of the data transmitted by the communication module at different distances in the water, according to the declination angles of the x-, y-, and z-axes of the control gyro, in the case of a certain initial position, the measurement of the virtual robot and the straight line distance enables the two robots to cooperate according to a preset target, so as to achieve the same goal [22]-[24]. Through the gyro sensor, the angle, angular velocity and angular acceleration information can be collected in real time and transmitted to the main controller in order to control the motors and adjust the walking path [25].

A. Analysis of underwater motion



(a) Acceleration curve of x-, y- and z-axis



(b) Angle curve of x-, y- and z-axis

Fig. 5. Acceleration and angle curve of x-, y-, z-axis in state of 45 degree (red: x-axis, blue: y-axis, green: z-axis)

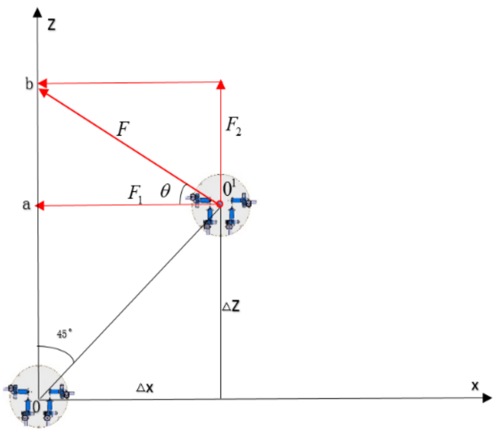


Fig. 6. Thrust compensation of the cooperative spherical robot

According to the information collected the x-, y- and z-axis acceleration, angular velocity, and angle from the gyroscope, the serial output response data information also can be used to analyze the control algorithm using the C program. The serial port prints the information [26]- [28]. From the Fig. 6, we can know that the values of Δx and Δz that can be obtained from the gyroscope. The motion time to object "t" is obtained by the processor timer, so it can be derived [29]:

$$\Delta x = at^2/2 \tag{1}$$

$$a = \frac{\sqrt{F_1^2 + F_2^2}}{m} \tag{2}$$

"a" is acceleration in the z-axis direction, calculate by the resultant force in the x-axis and z-axis directions. "F_1"and "F_2" is the thrust provided by the motor [30], "θ" is the deviation from the x-axis direction can be obtained by a gyroscope, so it can be derived that the distance and offset trajectory to the straight track, we can be deduced:

$$s = at^2 \cos\theta / 2 \tag{3}$$

According to the relationship between acceleration and distance can be derived from the normal track time "t".

$$t = \sqrt{2s / \sqrt{a_1^2 + a_2^2}} \tag{4}$$

B. Water-jet thrust test

According to the time and distance of the spherical robot motion that can return to a straight line, the pulse width modulation method can be used to accurately control the running time of the servo motor according to the offset data obtained by the gyroscope, so as to achieve the goal to realized controlling the stability [31]-[33]. By changing the direction of the servo motor on the leg, different angles of the underwater thruster can be controlled. The thruster is a miniature water-jet model, due to different driving voltages, the water-jet will produce different thrust, the maximum input voltage is 12 V [34]- [36], since the stability needs to know the datas of F_1 and F_2, the underwater thrust test is performed to obtain the functional relationship between the voltage and thrust to achieve precise path control.

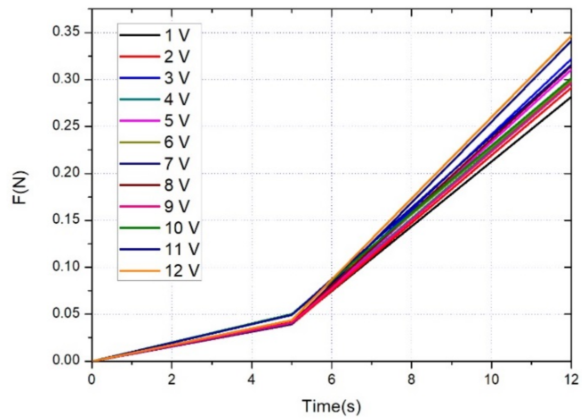


Fig. 7. The curve of different voltage and thrust contrast

During this experiment, by way of giving a different set of voltage values as the input quantity, and the thrust value generated by the motor water spray is used as the output value. During the experiment, we fixed the propeller to the bottom of a lever. The top of the lever is connected to a horizontal support. When the voltage is given, the propeller will generate a thrust to push the lever and the vertical deriction, declination angle is generated in the straight direction. By measuring the declination value, the thrust force is deduced using force decomposition and balance. In order to reduce the sample error, we take three angles of 0°, 30°, and 60° in this experiment. The formulas for the thrust force are respectively calculated $F_G = mgsin\varphi$, $F_G = mgsin\varphi$, $F_G = 2mgsin\varphi$ and then averaged.

Fig. 7 shows the experimental platform for the waterjet propulsion. The main controller is composed of ardunio, voltage regulator module, DC power module, water jet propeller and platform. In the experiment, in order to reduce the error, a total of 12 different voltages were selected as input from 0 ~ 12 V, and the four water-jets thrusters were respectively tested. At the same time, each thruster selected three angles, 0° , 30° and 60°, so a total of 12 sets of sample data were generated.

IV. Experimental results

The experiment is divided into two parts: the first part is that the two amphibious robots advance vertically to the target at a fixed distance. The second part is the advancement of the two robots to the target at a horizontally fixed distance. The basic principle is that the robot can realize the walking through the stable control system , and the gyro controls the x-axis, the y-axis and the z-axis deflection angle and controls the linear direction in real time through the judgment program. The method of measuring the distance is to predict the interval position of the two robots by the time delay of the communication modules with different distances. This method has the advantage of controlling the real-time detection distance at different angles and directions. No matter whether the coordinates of the two robots are the same, the distance between the two spherical robots can be obtained. The disadvantage is that the method of data delay is not suitable for the occasions with high precision movement. The method of ensuring constant communication accuracy is that the voltage of the module must be constant at 16 V, so in the design of the

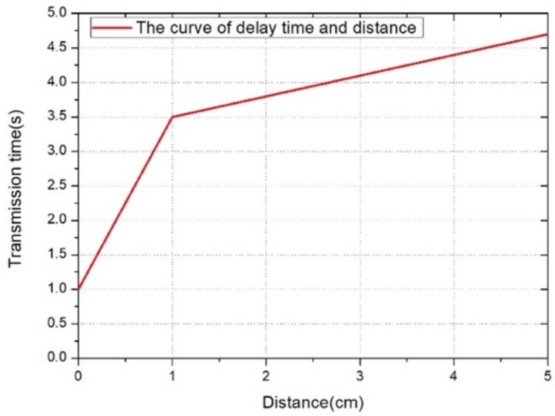


Fig. 8. The relationship of the distance and delay time

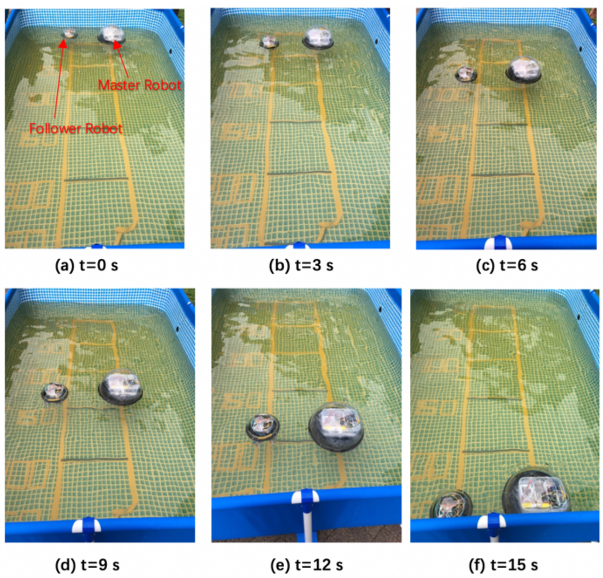


Fig. 9. Two robots horizontal collaborative experiment

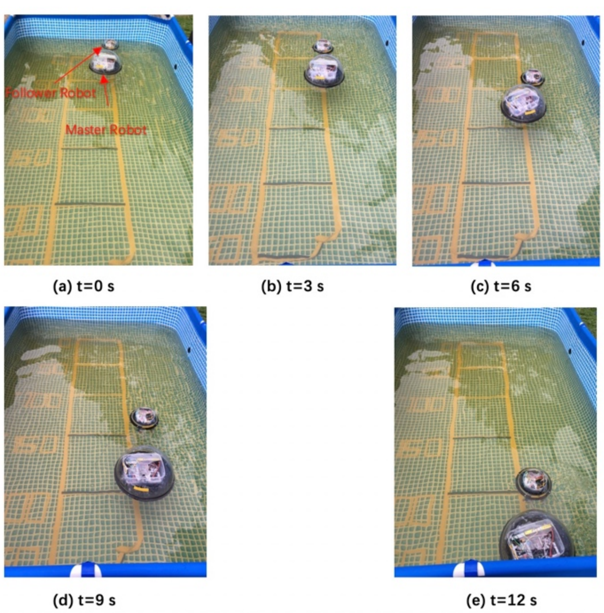
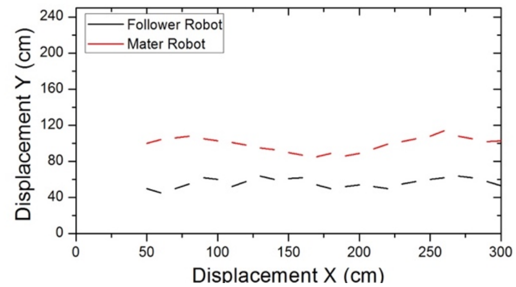
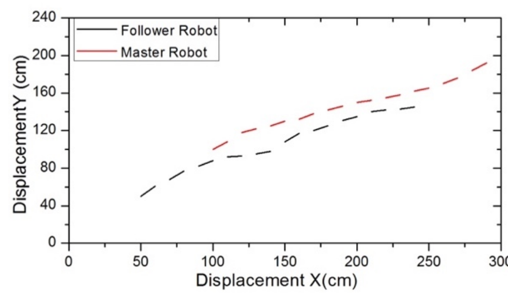


Fig. 10. Two robots vertical collaborative experiment



(a) Two robots collaborate vertically experimental



(b) Two robots collaborate horizontally experimental

Fig. 11. Robot cooperative motion track

power supply system, the robot needs three 8 V power supplies, one power supply to the control board, the gyro and the motor. The other two series connected batteries supply power to the communication module separately. After actual testing, the curve of distance and communication delay is shown as in Fig. 8. The actual experimental are shown in the Fig. 9-10. The underwater experiment mainly tests the distance between the two robots by 300 cm, as shown in Fig. 11, the following robot firstly performs the virtual robot positioning and the fixed position of the isosceles triangle. The main function of the virtual robot is to realize the spatial positioning reference. The robot starts to move, at the same time, the communication module starts to send data to the following robot, and the follower robot receives the data. The follower robot calculates the delay time by the processor through the serial port. The four control directions of the motor start under the control of the gyro sensor. Follow the master robot to walk straight, the follower robot need to update the position in real time, and feed back to the main controller. The program sets the master robot to perform distance positioning calibration every 10 s in order to avoid excessive distance error in the process of following the cooperation.

V. Conclusions

In this paper, the communication and stability control module used to model the time of communication transmission, the information and position coordinate are collected in real time in order to two amphibious spherical robots can cooperate with each other. According to the experimental results, two robots can realize horizontal and vertical cooperative motion to the specified target. This paper also proposes an advanced robotic cooperative control algorithm and analyzes the dynamic system of the amphibious spherical robot and conducts mechanical analysis to obtain the vector thrust of the adjustment direction, which lays a foundation for realized multi-robot hunting function.

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REFERENCES

[1] H. Xing, S. Guo, L. Shi, X. Hou, S. Su, Z. Chen, Y. Liu, H. Liu, "Performance Evaluation of a Multi-Vectored Water-Jet Propellers Device for an Amphibious Spherical Robot," *in Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp.1591-1596, 2018.

[2] C. Yue, S. Guo, Y. Li and M. Li, "Bio-Inspired Robot Launching System for a Mother-Son Underwater Manipulation Task," *in Proceedings of 2014 IEEE International Conference on Mechatronics and Automation*, pp. 174-179, 2014.

[3] Y. Li, S. Guo and Y. Wang, "Design and Characteristics Evaluation of a Novel Spherical Underwater Robot," *Robotics and Autonomous Systems*, vol. 94, pp. 61-74, 2017.

[4] L. Zheng, S. Guo, S. Gu, " Structure Improvement and Stability for an Amphibious Spherical Robot", *in Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp.1586-1590, 2018.

[5] Q. Pan, S. Guo and T. Okada, "A Novel Hybrid Wireless Microrobot," *International Journal of Mechatronics and Automation*, vol. 1, no. 1, pp. 60-69, 2011.

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

[7] S. Gu, S. Guo, L. Zheng, "Characteristic Evaluation of the Mobile Acoustic Communication for Spherical Underwater Robots (SUR III) ," *in Proceedings of 2018 IEEE International Conference on Mechatronics and Automation*, pp.2191-2196, 2018.

[8] S. Gu, S. Guo, L. Zhang, Y. Yao, " A Hybrid Propulsion Device for the Spherical Underwater Robot (SUR III) ," *in Proceedings of 2017 IEEE International Conference on Mechatronics and Automation*, pp.387-392, 2017.

[9] S. Gu, S. Guo, "Performance Evaluation of a Novel Propulsion System for the Spherical Underwater Robot (SUR III) ," *Applied Sciences*, vol.7, no. 11, 2017.

[10] S. Guo, Y. He, L. Shi, S. Pan, K. Tang and P. Guo, "Modal and fatigue analysis of critical components of an amphibious spherical robot," *Microsystem Technologies*, pp. 2233-2247, 2017.

[11] S. Guo, Y. Liu, L. Shi, P. Guo, H. Xing, X. Hou, and H. Liu, "Binocular Camera-based a Docking System for an Amphibious Spherical Robot," *in Proceedings of 2018 International Conference on Mechatronics and Automation (ICMA)*, pp. 1621-1626, 2018.

[12] L. Zheng, S. Guo, and S. Gu, "The communication and stability evaluation of amphibious spherical robots," *Microsystem Technologies*, pp. 1-12, 2018.

[13] Y. He, S. Guo and L. Shi, "3D Printing technology-based an Amphibious Spherical Underwater Robot," *in Proceedings of 2014 IEEE international conference on mechatronics and automation,* pp. 1382-1387, 2014.

[14] S. Guo, S. Pan, X. Li, L. Shi, P. Zhang, P. Guo and Y. He, "A system on chip based real-time tracking system for amphibious spherical robots," *Robotics and Computer–Integrated Manufacturing*, vol. 14, pp. 1-19, 2017.

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

[16] Y. Li, S. Guo and C. Yue, "Preliminary Concept and Kinematics Simulation of a Novel Spherical Underwater Robot," *in Proceedings of 2014 IEEE International Conference on Mechatronics and Automation*, pp. 1907-1912, 2014.

[17] X. Lin, S. Guo, C. Yue and J. Du, "3D Modelling of a Vectored Water Jet-Based Multi-Propeller Propulsion System for a Spherical Underwater Robot," *International Journal of Advanced Robotic Systems*, vol. 10, no. 1, pp. 1-8, 2013.

[18] H. Ren, C. Bai, Q. Kong, M. Baptista and C. Grebogib, "A chaotic spread spectrum system for underwater acoustic communication," *Statistical Mechanics and its Applications*, vol.478, no. 3, pp. 77- 92, 2017.

[19] F. Yuan, Q. Wei. and E. Cheng, "Multiuser chirp modulation for underwater acoustic channel based on VTRM," *International Journal of Naval Architecture and Ocean Engineering*, vol. 9, no. 3, pp. 256-265, 2017.

[20] D. Scaradozzi, G. Palmieri, D. Costa and A. Pinelli, "BCF Swimming Locomotion for Autonomous Underwater Robots: A Review and a Novel Solution to Improve Control and Efficiency," *Ocean Engineering*, vol. 130, pp. 437-453, 2017.

[21] K. Wang, Y. Liu and L. Li, "Visual servoing trajectory tracking of nonholonomic mobile robots without direct position measurement," *IEEE Transactions on Robotics*, vol. 30, pp. 1026-1035, 2014.

[22] L. Shi, Y. He, S. Guo, Kudo. H, M. Li and Asaka. K, "IPMC actuator-based a movable robotic Venus flytrap," *in Proceedings of 2013 ICME international conference on complex medical engineering (CME)*, pp 375-378, 2013.

[23] C. Yue, S. Guo and L. Shi, "Hydrodynamic Analysis of the Spherical Underwater Robot SUR-II," *International Journal of Advanced Robotic Systems*, vol. 10, no. 247, pp. 1-12, 2013.

[24] Y. Li, S. Guo and C. Yue, "Study on the Control System of a Novel Spherical Underwater Robot," i*n Proceedings of 2015 IEEE International Conference on Mechatronics and Automation*, pp. 2100-2105, 2015.

[25] S. Guo, S. Mao, L. Shi, Y. He, S. Su, Z. Chen and X. Hou, "Development of an Amphibious Mother Spherical Robot Used as the Carrier for Underwater Microrobots," *in Proceedings of the International Conference on Complex Medical Engineering (CME)*, pp. 758-762, 2012.

[26] H. Xing, S. Guo and L. Shi, "Hybrid Locomotion Evaluation for a Novel Amphibious Spherical Robot," *Applied Sciences*, vol. 8, pp. 156-174, 2018.

[27] J. Guo, S. Guo and L. Li, "Design and characteristic evaluation of a novel amphibious spherical robot," *Microsystem Technologies*, vol. 23, pp. 1999-2012, 2017.

[28] Y. He, L. Shi, S. Guo, S. Pan and Z. Wang, "Preliminary mechanical analysis of an improved amphibious spherical father robot," *Microsystem Technologies*, pp. 1-16, 2016.

[29] S. Pan, L. Shi and S. Guo, "A Kinect-Based Real-Time Compressive Tracking Prototype System for Amphibious Spherical Robots," *Sensors*, vol. 15, pp. 8232-8252, 2015.

[30] S. Guo, Y. He, L. Shi, S. Pan, R. Xiao, K. Tang and P. Guo, "Modeling and experimental evaluation of an improved amphibious robot with compact structure," *Robotics and Computer–Integrated Manufacturing*, vol. 51, pp. 37-52, 2018.

[31] Y. He, L. Zhu, G. Sun, J. Qiao and S. Guo, " Underwater motion characteristics evaluation of multi amphibious spherical robots," *Microsystem Technologies*, vol. 25, no. 2, pp. 499-508, 2019.

[32] Y. He, S. Guo, L. Shi, H. Xing, Z. Chen, S. Su, " Motion Characteristic Evaluation of an Amphibious Spherical Robot," *International Journal of Robotics and Automation*, vol. 34 no. 3, 2019.

[33] X. Hou, S. Guo, L. Shi, H. Xing, Y. Liu, H. Liu, Y. Hu, D. Xia and Z. Li, "Hydrodynamic Analysis-Based Modeling and Experimental Verification of a NewWater-Jet Thruster for an Amphibious Spherical Robot," *Sensors*, vol. 19, no. 259, 2019.

[34] S. Ziaeefard, B. R. Page, A. J. Pinar, et al. "Effective turning motion control of internally actuated autonomous underwater vehicles," *Journal of Intelligent & Robotic Systems*, vol. 89, no. 1-2, pp. 175-189, 2018.

[35] Z. Zeng, L. Lian, K. Sammut, et al. "A survey on path planning for persistent autonomy of autonomous underwater vehicles," *Ocean Engineering*, vol. 110, pp. 303-313, 2015.

[36] H. F. Gasparoto, O. Chocron, M. Benbouzid, et al. "Magnetic design and analysis of a radial reconfigurable magnetic coupling thruster for vectorial AUV propulsion," i*n Proceedings of the IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society*, pp. 2876-2881, 2017.