

# Study on Movement Stability for the Spherical Amphibious Robot

Jian Guo<sup>1</sup> and Guoqiang Wu<sup>1</sup>

<sup>1</sup>Tianjin Key Laboratory for Control Theory & Applications in Complicated Systems and Biomedical Robot Laboratory  
Tianjin University of Technology  
Binshui Xidao 391, Tianjin, China  
jianguo@tjut.edu.cn; 996767824@qq.com

**Abstract** – In recent years, wheeled robots have get widely used and developed because of its advantages. But they also have some disadvantages, for example, they obviously can't be compared with the spherical amphibious robots on rough ground. The four-legged spherical amphibious robots can move quickly and smoothly on rough ground and have superior carrying capacity. This paper deeply analyzed the movement stability of spherical amphibious robot. We used Solid works to build the three dimensional model. Then we completed the definition and setting of the spherical amphibious robot model in ADAMS. We completed the design of the control system. Lastly, we carried out some experiment; we analyzed the experimental result and verified the validity of the structure. By compared different swing angle and movement cycle of the joints, we get the best swing angle and movement cycle of the robot.

**Index Terms** – *Amphibious spherical robot; Swing angle; Movement cycle; Movement stability;*

## I. INTRODUCTION

Researches of the amphibious spherical robots have been focused on by researchers around the world. With a high adaptive faculty, amphibious spherical robots can be used in broad applications including pipeline cleaning, submarine topography survey, samples collection, topography surveys, water-quality monitoring, sample collection, and recovering objects on land and underwater.

Snake-like robot is developed by Tokyo university of science and technology, it is equipped with cameras in head, can be used to seek in the ruins of the disaster victims, especially in earthquake-prone countries such as Japan, the robot is very useful [1]. In 2010, Manchester University started to make the research of amphibious spherical robot. S.Watson and P.N.Green develop a tiny autonomous underwater robot MKV. The sphere diameter of autonomous underwater robot is 0.15 meters, the propulsion system use six propeller, MKV has four degrees of freedom of movement [2]-[4]. Hawaii University has been developed a spherical underwater robot: Omni-Directional Intelligent Navigator, This spherical robot is mainly used for monitoring the water environment and underwater operations. The air quality is about 126 kg. There are eight propellers in robot, the robot with sonar sensors, pressure sensors and inertial navigation system [5] [6].

Shuxiang Guo<sup>1,2\*</sup>

<sup>2</sup>Intelligent Mechanical Systems Engineering Department  
Faculty of Engineering  
Kagawa University  
Takamatsu, Kagawa, Japan

\*Corresponding Author: guoshuxiang@hotmail.com

The amphibious spherical robot has been a useful tool in our daily life, the way to realize the control is the key to research robot. The problem of how to control the amphibious robots is related to many aspects. The most difficult point is mainly about the circumstance, where a great number of disturbances exist. The effects of various kinds of turbulence and uncertain factors are added to the difficulty of amphibious spherical robot control [7]-[9]. The resultant performance cannot satisfy our requirements when using some traditional methods to design the controller of amphibious spherical robots.

In the past, the design of the production, usually for conceptual design and product design first, then having the manufacture of the sample. All kinds of experiments to test the performance of the samples product whether meet the requirements. However, the experiment can cause damage to the product, and even completely damaged products, and then modify the sample and repeat experiment, caused a great economic waste. If the design and manufacturing cycle is too long, also can increase the product cost. The virtual prototype technology can make simulation for the real sample before the production of the real sample, so the technology greatly shortened the design cycle and reduced the cost.

Because the cost of the amphibious spherical robot prototype is too high, so a lot of project would make a virtual prototype simulation analysis before the construction of physical experiment prototype., Dr Wang, coming from Harbin industrial university has carried on the simulation analysis of the amphibious spherical robot, its calculation separately Simulated by ADAMS software, the model of amphibious spherical robot is model for other reptiles, Made a plan and analysis of the walk gait on Road walk straight, walk on and turn in the downhill for the amphibious spherical robot, and analyzed the joint force when the robot move in the ground [10]-[13]. The data provided the basis for the design of the experimental prototype.

In this paper, we made a deeply analyze by ADAMS for the spherical amphibious robot. In ADAMS, the four foot mechanical model is established, we carried out some experiment; we analyzed the experimental result and verified the validity of the structure of the spherical amphibious robot model. By compared different swing angle and movement cycle of the joints, we get the best swing angle and movement

cycle of the robot.

The paper introduces the experiment to compare the displacement in the Y axis of the centroid of the amphibious spherical robot. And get the best swing angle of the hip joint and movement cycle.

The paper is organized as follows. Some research about amphibious robots is introduced in section I. In section II, the structure of amphibious spherical robot is described. Section III introduces the coordinated simulation of the amphibious spherical robot. In section IV, the experiment and simulation results are present. Finally, in Section V, presents conclusions and future work.

## II. STRUCTURE OF AMPHIBIOUS SPHERICAL ROBOT

The amphibious spherical robot can walk on land and move under the water. An amphibious spherical robot can realize more degrees of freedom movement with actuator units, the work to analysis and control a system is to construct the mathematics model, which is an important method and precondition. If we want to realize underwater robot motion control precisely, it is necessary to know its model precisely.

### A. General Design

The amphibious spherical robot is shown as in Fig. 1. The amphibious robot consists of a sealed transparent upper hemispheroid, two transparent quarter spherical shells that can be opened and four actuating units. Each unit consists of a water-jet propeller and two servo motors [14]-[17]. They are perpendicular. The control circuits, power supply, and sensors are placed in the sealed upper hemispheroid, which is waterproof. The amphibious spherical robot can float up and float down depends on water-jet propeller. In addition, we can change the speed of the robot by adjusting the propeller thrust. The design of the amphibious spherical robot is shown in Fig. 1. The robot has two actuating modes: quadruped walking mode and water-jet propulsion mode.

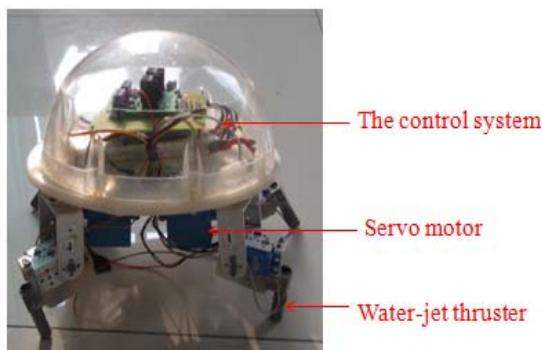


Fig. 1 Structure of amphibious spherical robot

On land, the amphibious spherical robot can implement walking. The horizontal servomotor actuates the water-jet propeller to swing forward. The water-jet propeller is swings forward and backward to complete walk on land. The spherical robot can walk with different velocities by changing the PWM signals.

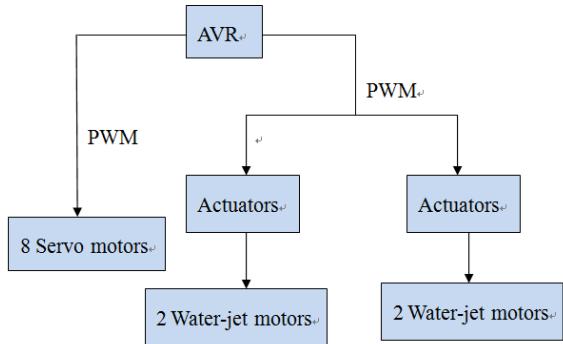


Fig. 2 The block diagram of the control system

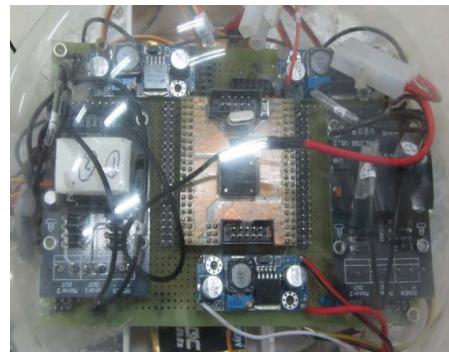


Fig. 3 The prototype of the control system

The block diagram of the control system for amphibious spherical robot is shown as in Fig. 2. And the prototype control system is show in Fig.3. An AVR micro unit is used as the CPU of the system for amphibious spherical robot, which generates PWM signal to control servo motors and water-jet motors with the four actuating units. In addition, it can change the state of the amphibious spherical robot. In order to adapt to underwater environment, It is also generates PWM signal to control the four water-jet motors. By adjusting the PWM signal, we can change both the direction and the size of water-jet thruster.

### B. Dynamics Modeling

We make the kinematics analysis for the amphibious spherical robot. Mainly analyzes the position and gesture for four legs of the amphibious spherical robot in the coordinate space, as well as the movement relationship between the position of four legs and the posture of the body. Its main content is divided into the analysis for forward kinematics and inverse kinematics.

If the parameters of each agency have be known, especially the parameters of leg rods, and the joint angles of the each movement joint has been given, the position and orientation of the robot which is relative to the based coordinate system can be determined [18]-[20].

We need to establish proper body fixed coordinate system in which the origin is located in the geometric center of the torso and set up the positive direction of X is the forward direction, the positive direction of Z opposite the gravity

direction, then the positive direction of Y can be obtained by right hand rule.

The robot completes cycle movement with crawling gait. When the robot is in crawling motion, one of the legs is in swing phase, the other three legs are in support phase, holding the whole robot. In this paper, we use the step sequence of LF → RB → RF → LB in Fig.4. In crawling, at least three legs are contacted on the ground and such conditions make it possible to generate statically balanced walking. Therefore, the implementation of this gait pattern is a better choice for the low-speed movement.

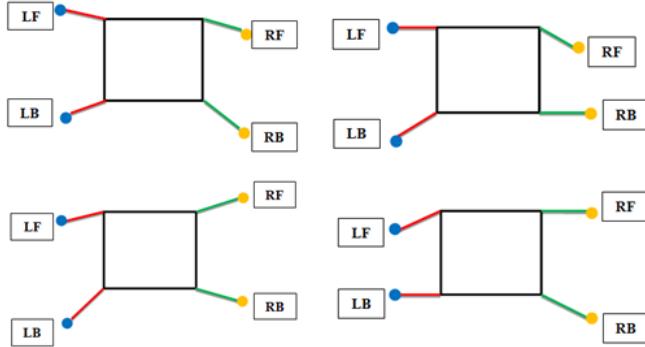


Fig.4 The crawling motion diagram of the spherical robot

### III. WALK GAIT SIMULATION OF THE SPHERICAL AMPHIBIOUS ROBOT

#### A. the Process of the Simulation

In this paper, the simulation of walk gait for the amphibious spherical robot used virtual prototype software ADAMS, we establish virtual prototype in the solid works 3d model, the constraint, drives and other parameters are added into the model through ADAMS software [21] [22]. In the process of simulation, the ADAMS soft provide 3d model and kinematics and dynamics Equation. The block diagram of the design system as shown below:

We establish the 3d model of the amphibious spherical robot by solid works as shown in Fig.7. Then we guide the model to the ADAMS software through ADAMS/Exchange connector, used to carry out the next steps.

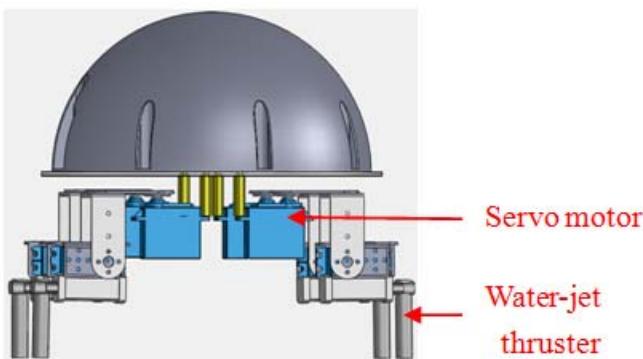


Fig.5 3d model of the amphibious spherical robot

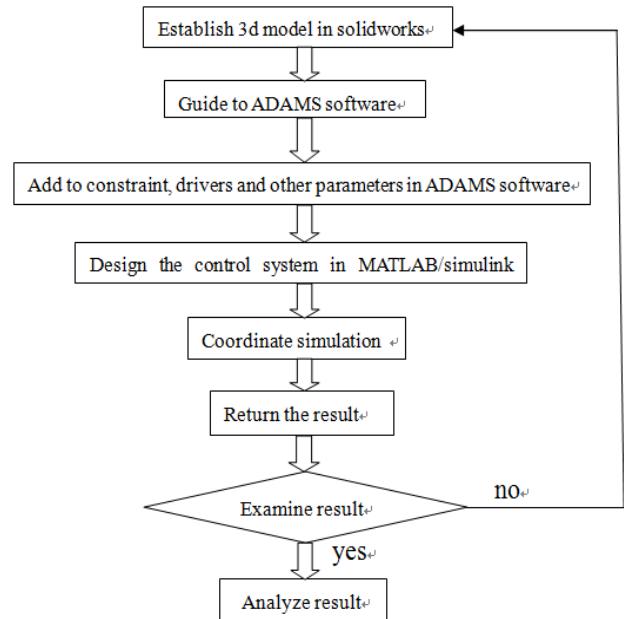


Fig.6 The flow diagram of simulation

#### B. Set the virtual prototype

. When we use this method guide the model into ADAMS, Each part of the model will have a loss of the model parameters such as the quality, centroid and rotational inertia, so we need to redefine the parameters of material of the model, in order to generate a new parameters.

In definition of the model material, we choose the aluminum alloy as the main material of model, when we complete the definition of the material of the model, the ADAMS software will be automatically generate the corresponding quality, centroid, moment of inertia and other related parameters for each part of the model.

The robot movement is driven by motor, now we need to append drive function to the eight servo motors. In the support process, both of them can produce contact force related to the speed. In order to achieve a better simulation result, we need to select contact function and contact friction parameters when set up the contact force in Fig.8. After parameters setting way is specified, the kinematic analysis can be carried out by applying the real load.

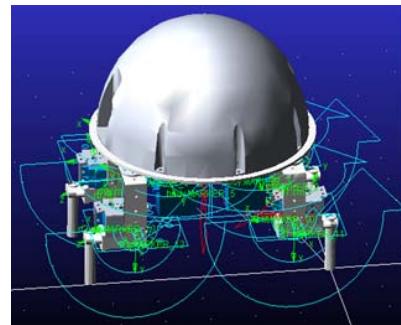


Fig.7 The simulation model of amphibious spherical robot in ADAMS

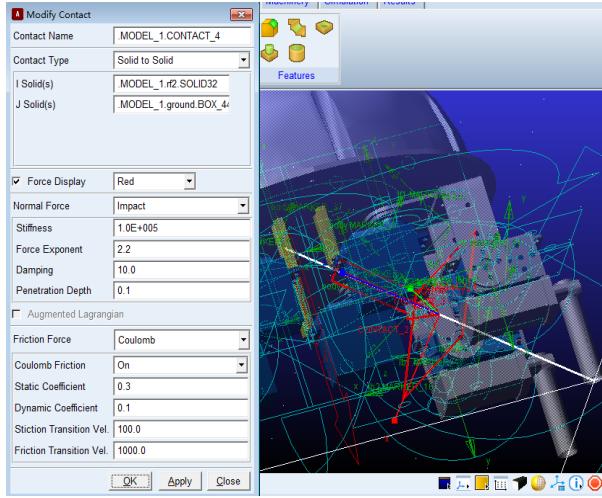


Fig.8 The definition dialog of contact force

The amphibious spherical robot has eight degrees of freedom. The hip joint between the body and legs has the rotation constraints; the rotation constraints of the hip joint ensure the legs can rotate around the body.

We add the rotation drive on the rotation constraints of the hip joint, as the drive of the amphibious spherical robot. After add the drive to the hip joint, the specific contents of the drive is not set in the ADAMS, we should establish the state variables in the ADAMS [23]-[25].

There were a total of four drives for hip joint, and at the same time we should build up four state variables, named VARIABLE-LF, VARIABLE-RF, VARIABLE-LB, and VARIABLE-RB respectively, after the completion of state variables, we should associate four state variables with the drives.

After the completion of the setup of input variable, we should have the setting of the output variable. Output variable is the results of simulation by ADAMS, and the control system sends the results through the input variables into ADAMS, then it provides drive for model. We create s1, s2, s3 as the output variable, corresponding to the displacement component in the X, Y and Z axis of centroid respectively [26] [27].

We also should set the contact force and friction, the end of the foot intermittent contact with the ground, so there will produce the contact force and friction force, and make the amphibious spherical robot advance normally, but it also has a considerable effect on the stability of the amphibious spherical robot. So when the end of foot contact with the ground, we should modify the parameters of the contact surface, only in this way, can we make the contact force close to the real contact. The Settings of the contact force as shown in table 1.

When the above step is completed, the basic setup of the ADAMS is completed. Next, make the model in the ADAMS as a separate module import to calculate.

We make the model imported into ADAMS, and we completed the setting and definition of the parameters of the amphibious spherical robot in ADAMS,

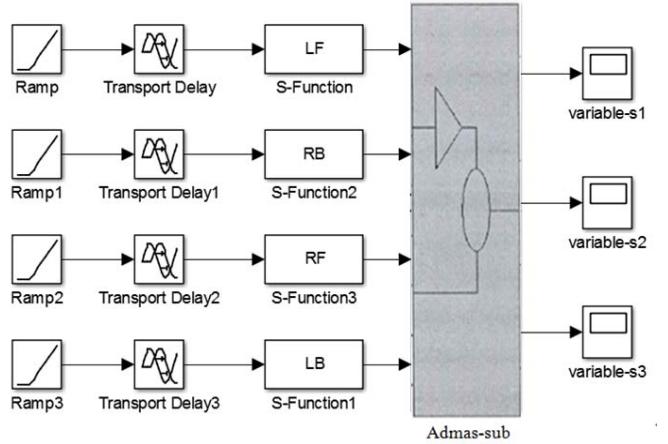


Fig.9 The block diagram of control system

TABLE I  
The parameters of the contact

Contact Type	Solid to Solid
Friction Type	Coulomb Friction
Stiffness	350000
Damping	350
Static Coefficient	0.3
Dynamic Coefficient	0.1
Friction Transition Velocity	1000
Stiction Transition Velocity	100

#### IV. EXPERIMENTS AND RESULTS

After finish the above Settings, we can do the gaits simulation of the amphibious spherical robot. The simulation results are expected to a smooth speed in the process of move forward for the amphibious spherical robot. The robot can keep walking straight in the forward direction and the offset is small relative to the forward direction. The displacement of the center of mass of the body in vertical direction is small; there will not be the phenomenon of jolt in vertical direction [28]-[31].

##### A. The movement experiments of robot

The displacement in the Y direction shows the bounce of the center of mass for the amphibious spherical robot, the displacement suggests the offset of the amphibious spherical robot in vertical direction when move along the trajectory.

We also have carried out some experiments of robot crawling; the displacement in the Y direction is obtained by the dividing rule, the experiments shown in figure 10.

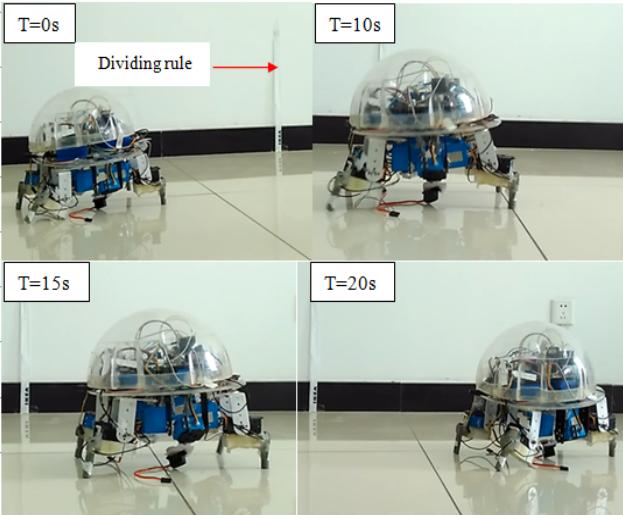


Fig.10 The experiment of robot crawling

### B. Experimental results

#### 1) Adjust the movement cycle

In order to get a well movement cycle of the amphibious spherical robot; we set different movement cycle and compared the results of the experiment. Now we set movement cycle are 0.1s, 0.2s and 0.3s, we compared the displacement in the Y axis of the center of mass for the amphibious spherical robot in different parameters. The result is shown in figure.11. The red curve represents the displacement in the Y axis of the centroid of the amphibious spherical robot when the movement cycle is 0.3s, the green and black curve represent the displacement in the Y axis of the centroid when the movement cycle is 0.1s and 0.2s respectively.

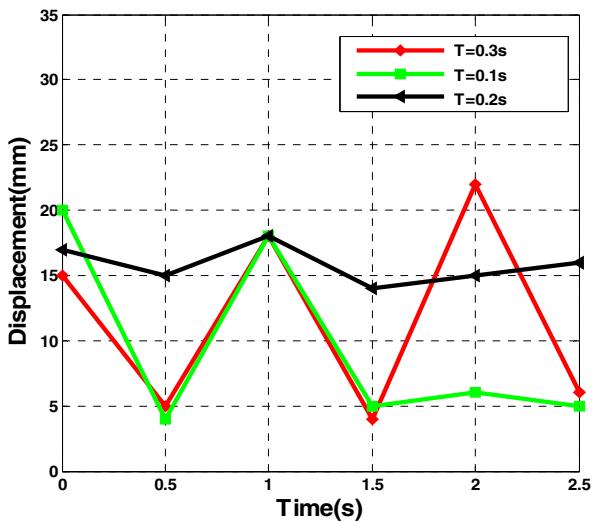


Fig .11 The graph of the displacement in the Y axis of the centroid in different operation cycle

The displacement in the Y axis expresses the degree of turbulence of the centroid for the amphibious spherical robot. We can see from the figure.11, when the operation cycle is 0.2s, the maximal displacement in the Y axis is smallest, and so we select 0.2s as the best operation cycle of the robot.

#### 2) Adjust the swing angle

In order to optimize the movement amplitude of the joint, we compared different swing angle of the joint. Now we set the swing angle of the hip joints are  $20^\circ$ ,  $30^\circ$  and  $40^\circ$  respectively, then we pick out the optimal parameters of the swing angle, the movement curve of the centroid of the amphibious spherical robot as shown in figure.12. The red curve represents the displacement in the Y axis of the centroid of the amphibious spherical robot when the swing angle of the hip joint is  $30^\circ$ , the green and black curve represent the displacement in the Y axis of the centroid when the swing angle of the hip joint is  $40^\circ$  and  $20^\circ$ .

Compared the displacement in the Y axis of the center of mass for the amphibious spherical robot, we can see in figure.12. When the swing angle is  $30^\circ$ , the maximal displacement in the Y axis is smallest. So the best swing angle of the hip joints is  $30^\circ$ .

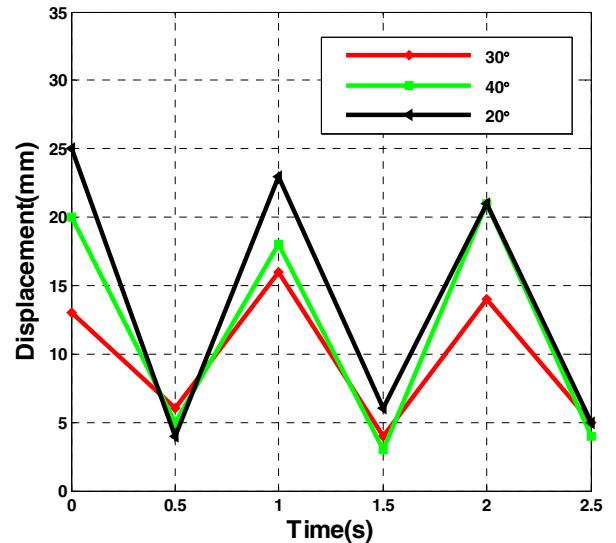


Fig .12 The graph of the displacement in the Y axis of the centroid in different swing angle of the hip joint

### V. CONCLUSION AND FUTURE WORK

In this paper, we set up the 3d model of the amphibious spherical robot in the solid works, and make the model imported into ADAMS, we completed the setting and definition of the parameters of the amphibious spherical robot in ADAMS, then we carried out the experiment and analyzed the experimental results, and got the best swing angle of the hip joint and movement cycle, at the same time; the validity of the structure design of the amphibious spherical robot was verified.

We can take other method to verify the stability of the amphibious spherical robot, and the stability of the amphibious spherical robot in the water will be considered in future work.

#### ACKNOWLEDGMENT

This research is partly supported by National Natural Science Foundation of China (61375094), Key Research Program of the Natural Science Foundation of Tianjin (13JCZDJC26200), and National High Tech. Research and Development Program of China (No.2015AA043202)

#### REFERENCES

- [1] Shuxiang Guo, Fu Wan, Wei Wei, et al. "An underwater microrobot with six legs using ICPF actuators", Proceedings of 2013 ICME International Conference on Complex Medical Engineering, pp.532-535, 2013.
- [2] Shuxiang Guo, Maoxun Li, Liwei Shi, et al. "A Smart Actuator-based Underwater Microrobot with Two Motion Attitudes", Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation, pp.1675-1680, 2012.
- [3] Xichuan Lin, Shuxiang Guo, et al. "Development of a spherical underwater robot", Proceedings of the 2011 IEEE/ICME International Conference on Complex Medical Engineering, pp. 662- 665, 2011.
- [4] Elena Garcia, Maria Antonia Jimenez, Pablo Gonzalez De Santos, Manuel Armada, "The evolution of robotics research", IEEE Robotics and Automation Magazine, Vol.14, No.1, pp.90-103, 2010.
- [5] Shuxiang Guo, Shilian Mao, Liwei Shi, et al. "Design and Kinematic analysis of an amphibious spherical robot", Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation, pp.2214-2219, 2012.
- [6] Liwei Shi, Shuxiang Guo, Kinji Asaka, "A novel multifunctional underwater microrobot", Proceedings of the 2010 IEEE International Conference on Robotics and Biomimetics, pp.873-878, 2010.
- [7] Yaxin Li, Shuxiang Guo, Chunfeng Yue, "Preliminary Concept and Kinematics Simulation of a Novel Spherical Underwater Robot". Proceedings of 2014 IEEE International Conference on Mechatronics and Automation, pp.1907-1921, 2014.
- [8] Liwei Shi, Shuxiang Guo, Shilian Mao, et al. "Development of an amphibious turtle-inspired spherical mother robot", Journal of Bionic Engineering, Vol.10, No.4, pp.446-455 2013.
- [9] Simon A. Watson, Dominic J. P. Crutchley, Peter N. Green, "The mechatronic design of a micro-autonomous underwater vehicle ( $\mu$ AUV)", International Journal of Mechatronics and Automation, Vol.2, No.3, 157-168, 2012.
- [10] Kuu-young Young, Jin-Jou Chen, "Implementation of a Variable D-H Parameter Model for Robot Calibration Using an FCMAC Learning Algorithm", Journal of Intelligent and Robotic Systems, Vol.24, No.4, pp.313-346, 2010.
- [11] Chunfeng Yue, Shuxiang Guo, Xichuan Lin, "Analysis and improvement of the water-jet propulsion system of a spherical underwater robot", Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation, pp. 2208-2213, 2012.
- [12] Shuxiang Guo, Shilian Mao, Liwei Shi, et al. "Design and Kinematic analysis of an amphibious spherical robot", Proceedings of the 2012 IEEE International Conference on Mechatronics and Automation, pp.2214-2219, 2013.
- [13] Liwei Shi, Yanlin He, Shuxiang Guo, "Skating motion analysis of the amphibious quadruped mother robot", Proceedings of the 2013 IEEE International Conference on Mechatronics and Automation, pp.1749-1754, 2013.
- [14] Shourov Bhattacharya, Sunil K. Agrawal, "Spherical rolling robot: a design and motion planning studies", IEEE Transactions on Robotics and Automation, Vol.16, No.6, pp.835-839, 2010.
- [15] Chunfeng Yue, Shuxiang Guo, Maoxun Li, "ANSYS Fluent-based modeling and hydrodynamic analysis for a spherical underwater robot", Proceedings of the 2013 IEEE International Conference on Mechatronics and Automation, pp.1577-1581, 2013.
- [16] Xichuan Lin and Shuxiang Guo, "Development of a spherical underwater robot equipped with multiple vectored water-jet-based thrusters", Journal of Intelligent and Robotic Systems, Vol. 67, pp. 307-321, 2012.
- [17] Chunfeng Yue, Shuxiang Guo, Liwei Shi, "Hydrodynamic analysis of the spherical underwater robot SUR-II", International Journal of Advanced Robotic Systems, Vol.10, pp.1-12, 2013.
- [18] Shuxiang Guo, Shilian Mao, Liwei Shi, et.al. "Development of an amphibious mother spherical robot used as the carrier for underwater microrobots", Proceedings of the 2012 ICME International Conference on Complex Medical Engineering, pp.758-762, 2012.
- [19] Shaowu Pan, Liwei Shi, Shuxiang Guo, "A Kinect-based Real-time Compressive Tracking System for Amphibious Spherical Robots", Sensors, Vol.15, no.4, pp.8232-3252, 2015.
- [20] Zhuang Ming, Yu Zhiwei, Gong Daping, et al, "Gait planning and simulation of quadruped robot with hydraulic drive based on ADAMS", Proceedings of the 2012 Machinery Design and Manufacture, pp.100-102, 2012.
- [21] Yixin Li, Shuxiang Guo, Chunfeng Yue, "Preliminary Concept of a Novel Spherical Underwater Robot, " International Journal of Mechatronics and Automation, Vol.5, No.1, pp.11-21, 2015.
- [22] Simon A. Watson, Dominic J. P. Crutchley, Peter N. Green, "The design and technical challenges of a micro-autonomous underwater vehicle ( $\mu$ AUV)", Proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, pp. 567-572, 2011.
- [23] Shuxiang Guo, Juan Du, Xiufen Ye, et al. "The computational design of a water jet Propulsion spherical underwater vehicle", proceedings of the 2011 IEEE International Conference on Mechatronics and Automation, pp. 2375-2379, 2011.
- [24] Xuewen Rong, Rui Song, Bin Li, "Simulation for Sagittal Plane Motions of a Quadruped Robot Using MATLAB and Simulink", Journal of Information & Computational Science, Vol.9, No.8, pp.2165-2173, 2012.
- [25] D. R. Yoerger, J. GSlotine Cooke, J.E. J. "The influence of thruster dynamics on underwater vehicle behavior and their incorporation into control system design", IEEE Journal of Ocean Engineering, Vol.15, No.3, pp. 167-178, 2012.
- [26] Shuxiang Guo, Yuehui Ji, Lin Bi, Xu Ma and Yunliang Wang, "A Kinematic Modeling of an Amphibious Spherical Robot System", Proceedings of 2014 IEEE International Conference on Mechatronics and Automation pp.1951-1956, 2014.
- [27] Ting M.C., M. Abdul Mujeebu, M.Z. Abdullah, M.R.Arshad, "Numerical study on hydrodynamic performance of shallow Underwater Glider Platform", Indian Journal of Geo-Marine Sciences, Vol.41, N0.2, pp.124-133, 2012.
- [28] Shuxiang Guo, Maoxun Li, Chunfeng Yue, "Underwater performance evaluation of an amphibious spherical mother robot", Proceedings of 2013 IEEE International Conference on Information and Automation, pp.1038-1043, 2013.
- [29] Fu Wan, Shuxiang Guo, Xu Ma, Yuehui Ji and Yunliang Wang, "Characteristic Analysis on Land for an Amphibious Spherical Robot", Proceedings of 2014 IEEE International Conference on Mechatronics and Automation, pp.1945-1950, 2014.
- [30] Shuxiang Guo, Xichuan Lin, et al. "Development and control of a vectored water-jet-based spherical underwater vehicle", Proceedings of the 2010 IEEE International Conference on Information and Automation, pp.1341-1346, 2010.
- [31] Xiaojuan Lan, Hanxu Sun, Qingxuan Jia, "Principle and dynamic analysis of a new-type spherical underwater vehicle", Journal of Beijing University of Posts and Telecommunications, Vol.33, No.3, pp.20-23, 2010.