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Passive and Active Attitude Stabilization Method for the Spherical Underwater Robot (SUR-II)

Chunfeng Yue, Shuxiang Guo, Maoxun Li, Yaxin Li

Abstract— **This paper introduces the passive and active attitude stabilization control for a spherical underwater robot (SUR-II). Due to the special structure of the robot, we involve passive attitude stabilization method both in pitch and roll directions. We adjust the distance between the center of buoyancy and the center of gravity to generate restoring moment. The restoring moment is used to realize passive attitude stabilization in pitch and roll directions. But for the yaw direction, because the robot is centrosymmetric and the water resistance is small and there is no restoring moment, active attitude stabilization control is necessary.**

For the active attitude stabilization, we employ Rotation Vector algorithm to instead Euler angle algorithm. The Euler angle algorithm decomposed the rotation motion into 3 orderly rotational motions in pitch, roll, yaw direction respectively. But the Rotation Vector algorithm can describe the rotation motion of the spherical underwater robot just in one time. It is very convenient to control the rotational motion. Finally, we carry out a stabilization experiment to verify the active attitude stability in yaw direction. The experimental results show that the robot can realize attitude stabilizaiton in a short time.

Keywords: Spherical Underwater Robot,Rotation Vector, Passive and active attitude stabilization.

I. Introduction

Autonomous Underwater Vehicle (AUV) has became a useful tool for many application fields such as ocean research, scientific investigation, ocean development, and underwater projects and etc. The shapes and sizes of AUVs depend on the underwater tasks. Different tasks require different shapes and sizes of AUVs. For example, a streamlined shape reduces water resistance and is preferable if the vehicle must move at high speeds [1-3]. But if underwater detection or operation tasks are the primary roles of an underwater robot, a non-streamlined shape is often used [4-6]. Deep-sea research requires high water-pressure resistance, while monitoring and observation tasks require small, flexible, and stable robots.

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Because of the central symmetry of spherical objects, spherical robots can realize rotational motion with a 0 degree turn radius. Many types of spherical underwater robots have been developed. ODIN-III was a typical prototype robot developed at the University of Hawaii [7, 8]. It had a metal shell, a diameter of 630 mm, 6 screw propellers installed outside the body, and a weight of 150 kg. This spherical underwater robot was used to monitor the environment and for underwater operations. An IMU was employed to realize attitude measurement.

Besides the large size spherical underwater robot, some Researchers at the University of Manchester and Oxford University co-developed a micro-spherical underwater robot [9-12]. This robot employed six propellers for its propulsion system; they were fixed around the equator of its spherical hull. The diameter is only 150 mm and a MEMS gyroscope is used to measure the angle in the yaw direction. This micro-robot was developed to monitor nuclear storage ponds to prevent leakage. Both of these robots used propellers on the outside of their bodies for their propulsion systems. Besides these research, there are other spherical underwater robots have used water-jet thrusters. Researchers at Harbin Engineering University developed a spherical underwater robot with three water-jet thrusters [13, 14]. However, the propulsive force of the thrusters was considerably reduced because the water input pipeline was curved. All of these spherical underwater robots cannot adjust attitude in pitch and roll direction actively. Researchers at the Beijing University of Post and Telecommunications developed a spherical underwater robot with one tunnel propeller [15]. This robot adjusted its attitude by changing its center of mass through a movable weight-balancing block. This made it possible to adjust the direction of the tunnel propeller and to achieve some linear motion, but the robot has a shortage which can not carry out more complex motions because it only had one propeller.

In our laboratory, we also developed a spherical underwater robot which was named as SUR-II. This robot used three vectored water-jet thrusters for its propulsion system [16–28]. One set vectored water-jet thruster is composed mainly of two components: one water-jet thruster and two servomotors. The water-jet thruster is driven by one high power DC motor. It provides the propulsive force and moment. The servomotors are employed to change the direction of the water-jet thruster. Each of a thruster owns 2 degrees of freedom, one is in the heave direction and another is in the horizontal direction. The robot can realize 3D motion by combining the three propulsive

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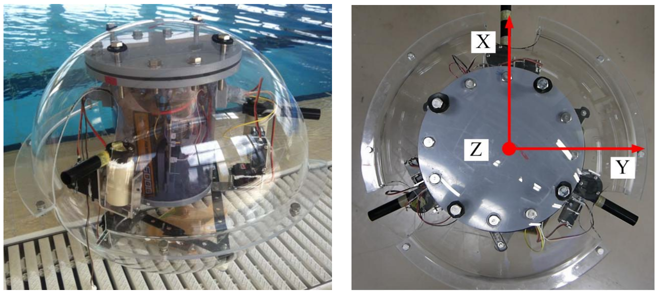
forces. In [23], Dr. Lin analyzed the propulsion system in detail. The propulsion system was assembled inside the spherical hull to reduce its effects on robot flexibility and to limit damage from possible impacts as shown in Fig. 1. The body coordinates system XYZ is defined in the Fig 1 (b). Because the robot is centrosymmetric, we just selected one of the thrusters as the head of the robot. The other two provided the propulsive force when the robot moves in horizontal direction.



(a) Side view (b) Top view

Fig. 1. The prototype of spherical underwater robot (SUR-II)

Attitude stability is a very important feature to an underwater robot, because all of the underwater tasks need a stable working condition. For underwater vehicle attitude stabilization, other researchers always selected passive method to balance the turbulence. In our research, besides the passive stabilization, we also want to realize active stabilization. The vectored water-jet thrusters will be used to active attitude stabilization. In addition, the torque of passive stabilization can be adjusted according to the user need.

The paper is organized as follows: The section II introduced the mechanical structure and the principle of passive stabilization. And then in the section III, the attitude measurement and active stabilization method were introduced in detail. After that an attitude stability experiment has been carried out in section IV. Finally, the conclusion and future work are listed in section V.

II. The Features of Spherical Underwater Robot

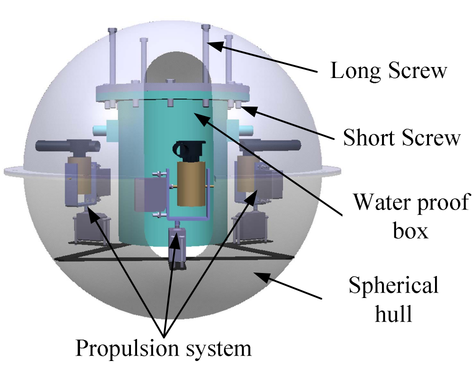
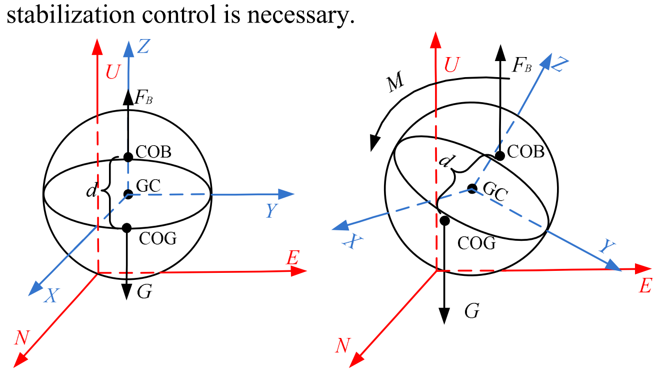


Fig. 2. The mechanical structure of SUR-II

The diameter of the spherical underwater robot (D) is 400mm, and the volume of the cylindrical waterproof box is ϕ 140mm by 200mm. The mechanical structure of the robot is shown in Fig.2. In the vertical direction, the waterproof box is supported by 4 long screws with 100mm. The cover of water-proof box is fixed by 8 short screws to avoid the water flow into the water proof box. A ring seal is also used to enhance sealing performance. The propulsion system is fixed on the triangular support. The propulsion system contains 3 vectored water-jet thursters. Each of the thruster has 2 rotational degrees of freedom. The range of rotation from −90 to +60 degrees in the vertical direction. The range of rotation from −30 to +30 degrees in the horizontal direction.

In this robot, because the volume of water proof box is big and the weight is light, buoyancy is decided by the water proof box. The buoyancy forces are almost determined by the waterproof box. The position of water proof box can be adjusted by 4 long screws. Hence, the center of buoyancy is adjustable. It is that means d which is the distance between COB and COG is adjustable. The detail information shows in Fig.3(a). When the robot does the roll or pitch motion in the horizontal plane. The torque M will be generated to prevent the robot dumping. This is the passive stabilization method in pitch and roll direction. Because the centrosymmetric shape, in yaw direction, the robot cannot keep stable by itself. Active stabilization control is necessary.



(a) Stable state (b) pitch and roll state

Fig. 3. The passive stabilization principle (SUR-II)
XYZ is the body coordinate systems. ENU is the inertia coordinate system. COB is the center of buoyancy. GC is geometric center. COG is the center of gravity.The d is the distance between the COB and COG, M is the torque when the robot roll and pitch.

In the ENU coordinate system, we can describe the robot according to the following dynamic equation.

$$M\dot{v}+C(v)v+D(v)v+g(\Theta)=\tau \qquad (1)$$

Where M denotes the rigid body mass matrix and added mass, $C(v)v$ is the Coriolis force. $D(v)v$ is the hydrodynamic damping. $g(\Theta)$ is the restoring forces and moment. The gravitational and buoyancy forces are called restoring forces. The gravitational force G will act through the center of gravity $r_G=[x_G \quad y_G \quad z_G]^T$ of the robot. Similarly, the buoyant force F_B will act through the center of buoyancy $r_B=[x_B \quad y_B \quad z_B]^T$. In this paper, we will consider neutrally buoyant robots, $F_B=G$. We can get $g(\Theta)$ in (2) when we just consider the attitude of the robot.

$$g(\Theta)=\begin{bmatrix}(z_G G-z_B F_B)\cos\gamma\sin\theta\\(z_G G-z_B F_B)\sin\gamma+(x_G G-x_B F_B)\cos\gamma\cos\theta\\-((x_G G-x_B F_B)\cos\gamma\sin\theta)\end{bmatrix}$$
$$=G\begin{bmatrix}(z_G-z_B)\cos\gamma\sin\theta\\((z_G-z_B)\sin\gamma+(x_G-x_B)\cos\gamma\cos\theta)\\-((x_G-x_B)\cos\gamma\sin\theta)\end{bmatrix}\qquad(2)$$

Where $\Theta=[\theta\quad\gamma\quad\psi]^T$ is the attitude angle in ENU coordinate system.

The passive attitude stabilization also has some disadvantages. Because the direction of the gravity and buoyancy is in vertical, the direction of restoring moment can not be changed. But we also need the robot to do some pitch and roll motions. In that case, the restoring moment will become resisting torque. Therefore, restoring moment adjustment is very important to the flexibility of the robot. In this paper, the robot cannot adjust the distance between COG and COB in real time. The restoring moment just can be adjusted off-line. So we should consider the working environment before sending the robot on a mission.

III. ATTITUDE MEASUREMENT AND STABILIZATION

According to (2), we can know that the attitude angles must be obtained to realize closed-loop control on attitude stabilization. Attitude information contains 3 angles, pitch, roll and yaw.

A. Attitude calculation

In our previous research [32], we utilized MEMS IMU to realize data collection. The Euler angle algorithm which is the most easy method has been used to calculate the attitude angles $\Theta=[\theta\quad\gamma\quad\psi]^T$. The rotating motion of a rigid body can be decomposed into 3 orderly rotational motions in pitch, roll, yaw direction respectively.

$$C_G^1=\begin{bmatrix}\cos\psi & -\sin\psi & 0\\ \sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\qquad(3)$$

$$C_1^2=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\theta & \sin\theta\\ 0 & -\sin\theta & \cos\theta\end{bmatrix}\qquad(4)$$

$$C_2^B=\begin{bmatrix}\cos\gamma & 0 & -\sin\gamma\\ 0 & 1 & 0\\ \sin\gamma & 0 & \cos\gamma\end{bmatrix}\qquad(5)$$

$$C_G^B=C_2^B C_1^2 C_G^1=\begin{bmatrix}T_{11} & T_{12} & T_{13}\\ T_{21} & T_{22} & T_{23}\\ T_{31} & T_{32} & T_{33}\end{bmatrix}\qquad(6)$$

Where

$T_{11}=\cos\gamma\cos\psi+\sin\gamma\sin\psi\sin\theta$

$T_{12}=-\cos\gamma\sin\psi+\sin\gamma\cos\psi\sin\theta$

$T_{13}=-\sin\gamma\cos\theta$

$T_{21}=\sin\psi\cos\theta$

$T_{22}=\cos\psi\cos\theta$

$T_{23}=\sin\theta$

$T_{31}=\sin\gamma\cos\psi-\cos\gamma\sin\psi\sin\theta$

$T_{32}=-\sin\gamma\sin\psi-\cos\gamma\cos\psi\sin\theta$

$T_{33}=\cos\gamma\cos\theta$

According to (6), we can calculate the attitude information as shown in (7).

$$\begin{cases}\theta=\arcsin(T_{32})\\ \gamma=\arctan(-\dfrac{T_{31}}{T_{33}})\\ \psi=\arctan(\dfrac{T_{12}}{T_{22}})\end{cases}\qquad(7)$$

Because non commutativity of the three angles, if the robot wants to a given attitude according to the attitude information, it has to be rotated 3 times orderly. It is so inconvenient to control the robot. In another aspect, the Euler angle algorithm also has singularities.

Due to these two reasons, we want to describe the rotational motion of the robot as one time rotational motion. It means that the robot can be rotated to a goal attitude position just in one time.

B. Rotation Vector algorithm

In this paper, we employed Rotation Vector algorithm to describe the rotational motion of the spherical underwater robot from the original position to a goal position [29-33]. We used quaternion to describe the rotation vector

$$Q=q_0+q_1\vec{i}+q_2\vec{j}+q_3\vec{k}\qquad(8)$$

And we set

$$\begin{cases}q_0=\cos\dfrac{\theta}{2}\\ q_1=l\sin\dfrac{\theta}{2}\\ q_2=m\sin\dfrac{\theta}{2}\\ q_3=n\sin\dfrac{\theta}{2}\end{cases}\qquad(9)$$

so

$$\begin{aligned}Q&=\cos\frac{\theta}{2}+(l\vec{i}+m\vec{j}+n\vec{k})\sin\frac{\theta}{2}\\&=\cos\frac{\theta}{2}+u\sin\frac{\theta}{2}\end{aligned}\qquad(10)$$

Where θ is the rotation angle and $u=l\vec{i}+m\vec{j}+n\vec{k}$ is the rotation vector. According to (6), we can get the coordinate transformation matrix C_G^B.

$$C_G^B=\begin{bmatrix}q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2)\\ 2(q_1q_2+q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3+q_0q_1)\\ 2(q_1q_3-q_0q_2) & 2(q_2q_3-q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2\end{bmatrix}\qquad(11)$$

In order to calculate the rotation vector, we built the differential equation in (12).

$$\frac{dQ}{dt}=\frac{1}{2}\omega_B\otimes Q\qquad(12)$$

Where ω_B is the output of IMU. After resolving (12), the rotation vector Q can be obtained.

Based on the rotation vector Q, we can confirm the rotational angle θ and the rotational axis u . For the stabilization control, we just adjust the direction and size of the propulsive force to combine a resisting moment in the given plane which is decided by Q. The resisting moment will keep the attitude of the robot.

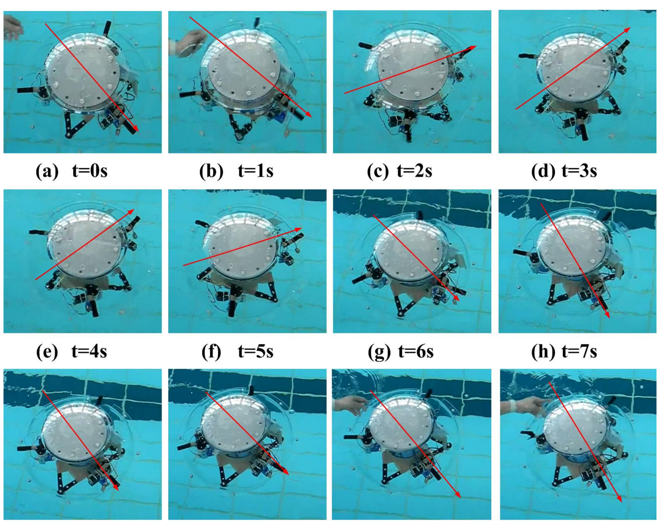
IV. EXPERIMENT

A simple underwater experiment is carried out to test the stability of the spherical underwater robot in yaw direction. In yaw direction, the robot restoring moment has no effect on the stability, so we can evaluate the active stabilization performance.

A. Stability in the yaw direction

As mentioned in the section II, the spherical underwater robot can realize passive stabilization in roll and pitch direction. But in the yaw direction, there is no restoring force and moment to balance the noise from the environment. And due to the spherical hull, the water resistance is also very small in yaw direction. Therefore, the robot can be affected by the external force easily.

The MEMS IMU sensor that has been mentioned in section II is employed to obtain the attitude information. Based on the sensor, the robot can realize active attitude control to overcome the water influence.



(a) t=0s **(b) t=1s** **(c) t=2s** **(d) t=3s**

(e) t=4s **(f) t=5s** **(g) t=6s** **(h) t=7s**

(i) t=8s **(j) t=9s** **(k) t=10s** **(l) t=11s**

Fig.4. Active stabilization experiment with time variables

As mentioned in the section II, the direction of thruster can be controlled in horizontal and vertical direction. In this experiment, we just control the direction of the thruster to adjust the propulsive force and moment. We put the robot in a pool, the robot keeps stable state in a given attitude in yaw direction. And then, we rotated the robot in the yaw direction by hand. The robot detects the angle difference. In order to keep the attitude in the given position, the robot will drive the propulsion system to generate the resisting moment. With the reducing of angle difference, the angle of the thruster will turn back to reduce the moment in yaw direction. Finally, the robot will stop at the original direction and the propulsion moment will also reduce to 0.

The experimental results (Fig. 5) showed that although the external force and moment made the robot rotate about 90 degrees, the response time of the SUR-II was just 10 seconds. Due to the small water resistance, the robot owned high flexibility.

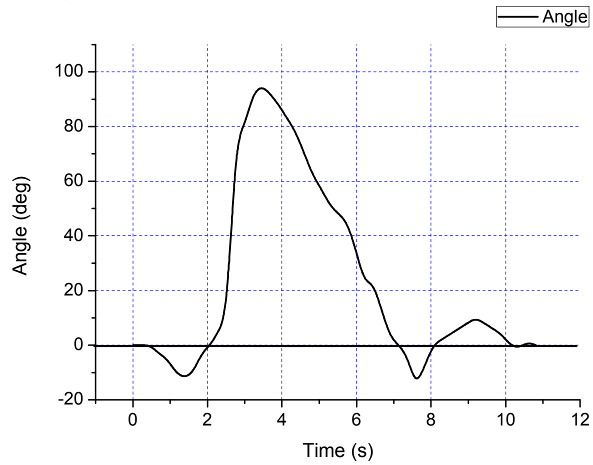


Fig. 5. The experimental result in yaw direction

V. CONCLUSION AND FUTURE WORK

In this paper, we focused on the passive and active attitude stabilization methods for the spherical underwater robot (SUR-II). To the passive attitude stabilization method, we realized restoring moment adjustment off-line to meet different working environment requirement. We employed 4 long screws to fix the water-proof box and adjust the restoring moment. The attitude angles of the robot had been calculated according to Euler Angle algorithm. But it was not convenient to control the robot directly, because the three angles had non-commutativity. We employed Rotation Vector algorithm to overcome these shortcomings. Finally, we carried out an active stabilization experiment in yaw direction, because there is no storing moment can affect the active attitude stabilization performance. The experiment results showed that even the external force was very strong, the adjustment time was less than 10 seconds.

In the future, we also want to enhance the performance of the attitude stabilization control. For the passive attitude stabilization, a real time restoring moment program is considering to adapt different environment. For the active attitude stabilization, high dynamic motion should be considered both in pitch and roll directions.

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