Study on the Control System of a Novel Spherical Underwater Robot

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Abstract—This paper presents the control system design for a novel spherical underwater robot (SUR). The two-level architecture control system is employed to realize sensor data collection, control algorithm realization, control command transmission, motor actuation and etc. TMS320F28335 and ATMEGA 2560 are taken as the master and slave processors respectively. Depth sensor and MEMS IMU are utilized to realize closed-loop control. In order to evaluate the response time and availability of the control system, the horizontal motion and vertical motion control experiment are carried out. Through these experiments, PID controller is used to control the servomotors. The experimental results show that the propulsion system can complete the action based on the direction controlling of the thruster.

Index Terms—Control system; Novel spherical underwater robot; Sensor data calibration; MEMS IMU

I. INTRODUCTION

With the development of underwater robotics and robot-related science and technology, the researches on underwater robots have made many remarkable achievements, at present, there are many countries in the world are committed to the research and development of underwater robots. Underwater robots show significant potential of being applied in the fields of industry, fishery, exploration, and military and so on. Underwater robots have become one of the most important tools to exploit and use marine resources. Therefore, unmanned underwater vehicles (UUVs) are developed rapidly due to their ability to access deep, dangerous, and confined areas unattainable by divers. Generally, the UUVs can be divided in two categories: Remotely-operated Vehicle (ROVs) and Autonomous Underwater Vehicle (AUVs). ROVs are unoccupied, highly maneuverable, and operated by a human operator. ROVs are linked to the ship by an umbilical cable. [1] An autonomous underwater vehicle (AUV) is a robot which travels underwater without requiring input from an operator. They always involve various underwater sensors i.e. compasses, depth sensors, sonars, magnetometers, thermistors, conductivity probes and Inertial Measurement Unit (IMU) to realize underwater navigation, data collection, and strategic decision. Different applications require different shapes, and sizes of AUVs. [2]

Due to the central symmetry, spherical objects always performance high stability and flexibility. Spherical robots can realize rotational motion with a 0 degree turn radius. Therefore, many researchers involved in this research topic and developed many spherical underwater robots. ODIN-III was a typical prototype robot developed at the University of Hawaii [3, 4]. The metal hull with a diameter of 630mm resisted water pressure. The propulsion system with 8 screw propellers installed outside the body provided propulsive forces. This spherical underwater robot was used to monitor the environment and underwater operations. It used a high accuracy IMU to realize attitude measurement. Besides the large size spherical underwater robot, University of Manchester and Oxford University co-developed a micro-spherical underwater robot to monitor nuclear storage ponds [5-8]. The micro robot installed six propellers around the equator as its propulsion system. The diameter of this robot was only 150mm. Therefore, a MEMS gyroscope was used to measure the angle in yaw direction. These two robots equipped propellers on the outside of their bodies for their propulsion systems. Besides propeller, tunnel thrusters are also attract the interests of researchers who have high requirements on the propeller. Du et al. developed a spherical underwater robot with water-jet thrusters [9, 10]. But the propulsive force of the thrusters was considerably reduced because the pipe was curved. All of these spherical underwater robots cannot adjust attitude in pitch and roll direction actively. Lan et al. at the Beijing University of Post and Telecommunications developed a spherical underwater robot that is only actuated by one tunnel propeller [11]. Based on a movable weight-balancing block, the attitude control was realized.

The control of underwater robots is one of the key technologies for these kinds of spherical underwater robots, and the control problems of SURs involve many aspects. The difficulty of underwater robot control lies in its working environment is underwater, underwater various disturbances and uncertainties, as well as the inconvenience of the experimental environment is bound to add the difficulty of underwater robot control. The resultant performance cannot satisfy our requirements when using some traditional methods to design the controller of underwater robots. Therefore, it is necessary to investigate more efficient and easy to implement motion control methods and control system. [12]

In our laboratory, the second-generation spherical underwater robot (SUR-II) which is actuated by three vectored water-jet thrusters for its propulsion system is developed [13-18]. The robot can realize 3 DOF motion. The propulsion system was assembled inside the spherical hull to reduce its
effects on the robot’s flexibility and to limit damage from possible impacts. But the second-generation Spherical Underwater Robot (SUR-II) which we have made has the problem of the high energy consumption. Based on this reason, we developed the novel spherical underwater robot (SUR). Figure 1 shows the prototype of the novel spherical underwater robot. The new structure of the robot takes four vectored water-jet thrusters as its propulsion system. [19] This paper presents the control system design of the novel SUR.

(a) Side view                                 (b) inside view

Fig. 1. The prototype of the novel spherical underwater robot

The organization of this paper is as follows. Related work is reviewed in section 1. Section 2 describes the Kinematics and Dynamics of the novel SUR. In this section, the attitude of the novel SUR is discussed in the quaternion space. Section 3 describes the details of the control system design for the novel SUR. The experiment for testing the motion characteristics and control performances are reported in section 4. Section 5 provides concluding remarks.

II. KINEMATICS AND DYNAMICS

An accurate kinematics and dynamic model is an essential factor for the robot control. In order to obtain the best control performance, the kinematics feature and the dynamic model are analyzed in this section.

A. Kinematics

Generally, as a rigid body, underwater vehicle has 6 DOF motions which are shown in Table I, it is a description of force and moment, velocities and position according to SNAME notation.

<table>
<thead>
<tr>
<th>DOF</th>
<th>Motion definition</th>
<th>Forces and moments</th>
<th>Linear and angular velocity</th>
<th>Position and Euler angles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Surge (motion in the x-direction)</td>
<td>$X$</td>
<td>$u$</td>
<td>$x$</td>
</tr>
<tr>
<td>2</td>
<td>Sway (motion in the y-direction)</td>
<td>$Y$</td>
<td>$v$</td>
<td>$y$</td>
</tr>
<tr>
<td>3</td>
<td>Heave (motion in the z-direction)</td>
<td>$Z$</td>
<td>$w$</td>
<td>$z$</td>
</tr>
<tr>
<td>4</td>
<td>Roll (rotation on x-axis)</td>
<td>$K$</td>
<td>$p$</td>
<td>$\phi$</td>
</tr>
<tr>
<td>5</td>
<td>Pitch (rotation on y-axis)</td>
<td>$M$</td>
<td>$q$</td>
<td>$\theta$</td>
</tr>
<tr>
<td>6</td>
<td>Yaw (rotation on z-axis)</td>
<td>$N$</td>
<td>$r$</td>
<td>$\psi$</td>
</tr>
</tbody>
</table>

1) Novel SUR’s Orientation by Euler Angles

To establish the Kinematics model, we should define two coordinate systems. The first coordinate system is the earth fixed coordinate system $\{E\}$. It is a handed cartesian coordinate. It defines one selected point $E$ as the original point and $n$ axis, $e$ axis and $d$ axis point north, east and down respectively. The second coordinate is body fixed coordinate system $\{B\}$. Because our robot is spherical shape, we define the geometric center as the origin of coordinates. The x-axis is parallel to one of the thruster. The y-axis is the axis of the waterproof box. According to handed caresitian coordinate, y-axis can be determined. Figure 2 shows the relationship between the two coordinate systems.

Fig.2 Geographic coordinate system and body fixed coordinate system

The position and orientation relative to the earth fixed coordinate system (North-East-Down $\{E\}$) can be represented as Equation (1).

As a rigid body, we define the two vectors $\eta, v \in \mathbb{R}^6$ as

$$\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \end{bmatrix} = \begin{bmatrix} x \\ y \\ z \\ \varphi \\ \theta \\ \psi \end{bmatrix}$$

(1)

$$v = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} u \\ v \\ w \\ p \\ q \\ r \end{bmatrix}$$

(2)

And we can get

$$v_1 = R_e^n \eta_1$$

(3)

$$v_2 = J_{k,\psi} (\eta_2) \hat{i}_2$$

(4)

We define $J_e \in \mathbb{R}^{6\times 6}$, therefore

$$v = J_e \hat{i}$$

(5)
Where
\[
J_e = \begin{bmatrix} R^E_B & 0_{3x3} \\ 0_{3x3} & J_{k,o} \end{bmatrix}
\] (6)

Where \( R^E_B \in \mathbb{R}^{3x3} \) is the rotation matrix expressing the transformation from the earth fixed coordinate system \{E\} to body fixed coordinate system \{B\}. Based on three orderly rotations, we can transform the attitude from \{E\} to \{B\}. And the transformation order is in the Figure 3.

Based on Figure 3, we can obtain the rotation order for the coordinate transformation:

\[
\begin{align*}
&\text{Rot}(\psi, z) \rightarrow \text{Rot}(\theta, y) \rightarrow \text{Rot}(\phi, x) \\
&\quad \Rightarrow R^E_B = R^E_z R^E_y R^E_x
\end{align*}
\]

And the transformation matrix as following:

\[
R^E_z = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}
\] (7)

\[
R^E_y = \begin{bmatrix} \cos \theta & 0 & -\sin \theta \\ 0 & 1 & 0 \\ \sin \theta & 0 & \cos \theta \end{bmatrix}
\] (8)

\[
R^E_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \phi & -\sin \phi \\ 0 & \sin \phi & \cos \phi \end{bmatrix}
\] (9)

and we know

\[
R^E_B = R^E_z R^E_y R^E_x
\] (10)

therefore

\[
R^E_z = \begin{bmatrix} \cos \theta \cos \psi & \sin \theta \sin \psi \cos \phi - \cos \phi \sin \psi & \sin \phi \sin \psi + \cos \phi \sin \theta \cos \psi \\ \cos \theta \sin \psi & \sin \theta \cos \psi \cos \phi + \sin \phi \cos \psi & \cos \phi \sin \psi + \sin \phi \sin \theta \cos \psi \\ -\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta \end{bmatrix}
\] (11)

The \( J_{k,o} \in \mathbb{R}^{3x3} \) can be expressed as in terms of Euler angles as

\[
J_{k,o} = \begin{bmatrix} 1 & 0 & -\sin \theta \\ 0 & \cos \phi & \cos \theta \sin \phi \\ 0 & \sin \phi & \cos \theta \cos \phi \end{bmatrix}
\] (12)

We know the \( J_{k,o} \) is an orthogonal matrix, \( J_{k,o}^{-1} = J_{k,o}^T \), and we can express the inverse matrix as

\[
J_{k,o}^{-1} = \frac{1}{\cos \theta} \begin{bmatrix} \cos \phi \sin \theta & \cos \phi \sin \theta & 0 \\ 0 & \cos \psi \cos \phi & \cos \psi \sin \phi \\ 0 & \sin \psi \cos \phi & \sin \psi \sin \phi \end{bmatrix}
\] (13)

Finally, we can express the \( \eta \) as

\[
\eta = J_{k,o}^{-1} v = \begin{bmatrix} 0 & 0 & 0 \\ \frac{1}{\cos \phi} \cos \psi \sin \theta & \frac{1}{\cos \phi} \cos \psi \sin \theta & 0 \\ 0 & \frac{1}{\cos \phi} \cos \psi \cos \phi & \frac{1}{\cos \phi} \cos \psi \sin \phi \end{bmatrix} v
\] (14)

2) Novel SUR’s Attitude by Quaternion

As we known, the Euler angle has singular solution. Therefore, quaternion is used to avoid the problem of singularity. A typical quaternion \( \varepsilon \) can be expressed as [20]:

\[
\varepsilon = \varepsilon_0 + \varepsilon_1 i + \varepsilon_2 j + \varepsilon_3 k
\] (15)

Where, \( \varepsilon_i (i=1,2,3,4) \) are scalars. The \( i, j \) and \( k \) are defined to satisfy the following combinatory rules:

\[
i i = j k = -1 ; i j = k , j k = i , k i = j ; j i = -k , k j = -i , i k = -j .
\]

where

\[
\begin{align*}
\varepsilon_0 &= \cos \frac{\theta}{2} \\
\varepsilon_1 &= \sin \frac{\theta}{2} \\
\varepsilon_2 &= \frac{1}{2} \sqrt{1 + m^2 + n^2} \\
\varepsilon_3 &= \frac{1}{2} \sqrt{1 - m^2 - n^2}
\end{align*}
\] (16)

therefore, we can get

\[
\varepsilon = \cos \frac{\theta}{2} + (i j + m j + n k) \sin \frac{\theta}{2}
\] (17)

Due to \( R^B_E = R^{E^{-1}}_B = R^{E^T}_B \). We can express \( R^B_E \) by (16) and

\[
R^E_B = \begin{bmatrix} \varepsilon_0^2 + \varepsilon_1^2 - \varepsilon_2^2 - \varepsilon_3^2 & 2(\varepsilon_0 \varepsilon_1 - \varepsilon_2 \varepsilon_3) & 2(\varepsilon_0 \varepsilon_3 + \varepsilon_1 \varepsilon_2) \\ 2(\varepsilon_1 \varepsilon_0 + \varepsilon_2 \varepsilon_3) & \varepsilon_0^2 - \varepsilon_1^2 + \varepsilon_2^2 - \varepsilon_3^2 & 2(\varepsilon_0 \varepsilon_2 - \varepsilon_1 \varepsilon_3) \\ 2(\varepsilon_2 \varepsilon_0 - \varepsilon_3 \varepsilon_1) & 2(\varepsilon_1 \varepsilon_2 + \varepsilon_0 \varepsilon_3) & \varepsilon_0^2 - \varepsilon_1^2 - \varepsilon_2^2 + \varepsilon_3^2 \\
\end{bmatrix}
\] (18)
For velocity analysis, the time derivative of the quaternion can be related to the angular velocity vector as
\[
\begin{bmatrix}
\dot{\epsilon}_0 \\
\dot{\epsilon}_1 \\
\dot{\epsilon}_2 \\
\dot{\epsilon}_3
\end{bmatrix} =
\begin{bmatrix}
0 & -\omega_z & -\omega_y & \omega_x \\
\omega_z & 0 & -\omega_x & \omega_y \\
\omega_y & \omega_x & 0 & -\omega_z \\
-\omega_x & -\omega_y & \omega_z & 0
\end{bmatrix}
\begin{bmatrix}
\epsilon_0 \\
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3
\end{bmatrix}
\] (19)

where, \(\Omega = [\omega_x \ \omega_y \ \omega_z]^T\) is the output of gyroscope sensor.

B. Dynamic Model

The dynamics of an underwater robot contain two parts. The first part is the rigid body forces and moment which can be described by Newton-Euler equation. Another part is the hydrodynamics forces and moments which are generated by the present of the fluid. And we assume that the generalized hydrodynamics forces on a rigid body can be linearly superimposed [21].

For a rigid body, many researchers have focused on the dynamic modeling. In [22], Andres El-Fakdi et al. established the dynamic model for the Ictineu AUV which is an open frame underwater robot. Roque Saltaren Pazmiño et al. developed a 6 DOF underwater parallel robot. They established the dynamic model for this multibody system [23]. Prof. J. Yuh et al. focus on the underwater robot control. They developed an omni-directional spherical underwater robot and established the dynamic model for it [24] [25].

Our robot also has spherical shape and can be simplified as a rigid body. Therefore, we establish the dynamic model as shown in Equation (20)

\[
M\ddot{v} + C(v)v + D(v)v + g(\theta) = \tau + \omega
\] (20)

where, \(M \in \mathbb{R}^{6 \times 6}\) is the mass matrix that includes body rigid body mass \(M_{RB}\) and added mass \(M_A\), \(M = M_{RB} + M_A\) ; \(C(v)v \in \mathbb{R}^6\) is the vector of Coriolis and Centrifugal terms including the added mass, \(C(v)v = (C_{RB}(v) + C_A(v))v\) ; \(D(v)v \in \mathbb{R}^6\) is the vector of friction and hydrodynamic damping terms, \(D(v)v = (D_f + D(v))v\) ; \(g(\theta) \in \mathbb{R}^6\) is the vector of gravitational and buoyant generalized forces; \(\tau \in \mathbb{R}^6\) is the vector of the forces and moments acting on the vehicle; \(\omega \in \mathbb{R}^6\) is the vector of the external forces and torques due to the waves and marine streams. Finally, we can rewrite the Equation (20) as:

\[
(M_{RB} + M_A)v + (C_{RB}(v) + C_A(v))v + (D_f + D(v))v + g(\theta) = \tau + \omega
\] (21)

In summary, a brief introduction to the fundamental concepts regarding underwater robots has been presented. After considering our robot, the dynamic model is established. All the principles and theories in this section will be the basis for the design of the robot control system.

III. DESIGN OF CONTROL SYSTEM

This section describes the design of control system for the novel SUR. Figure 4 presents the architecture of control system which is employed. A two-level architecture was utilized for the control system.

A. Design of the Control Circuit

The structure of the control circuit was designed using a master–slave configuration. Figure 5 shows the assumption diagram of the control circuit.

In summary, a brief introduction to the fundamental concepts regarding underwater robots has been presented. After considering our robot, the dynamic model is established. All the principles and theories in this section will be the basis for the design of the robot control system.
The master side was used for sensor data collection, control algorithm realization, and command transmission. The slave side was used to execute the commands from the master side and to drive the actuators to execute underwater missions.

B. Design of the Software System

The propulsive force could be controlled by the direction of the water-jet thrusters or by the magnitude of the forces exerted by the thrusters. We used a Proportional-Integral-Derivative (PID) controller to control the direction of the thrusters and enhance their flexibility. Figure 6 shows a simplified flow chart of the control strategy. For a given task, the robot first completed its system initialization, which involved initializing and calibrating the sensors. After initialization, the initial attitude angle, depth, and position were obtained. The robot then compared the current parameters with the target parameters. If the current parameters were not equal to the target parameters, the robot attempted to reduce the differences through motion by calculating a suitable trajectory.

![Fig.6 Block diagram of the control circuit](image)

IV. EXPERIMENTS AND RESULTS

Motion control of the novel SUR is a very challenging task because of the nonlinearity of the robot, time-variance, uncertain external disturbance and difficulty in hydrodynamic modeling. In order to achieve autonomy, the control system must have the adaptability and robustness to the nonlinearity and time-variance of the SUR dynamics, unpredictable environmental uncertainties such as current. The PID (Proportional-Integral-Derivative) type control and SMC (Sliding Mode Control) type control are the main methods in traditional control. SMC is a nonlinear feedback control scheme. It restricts the system motion in a certain subspace of the state space and makes it asymptotically converge to its equilibrium point, so it is robust to parameter variations and external disturbances. Due to the design and simplification of the novel SUR, the PID control strategy is selected for the controller of the novel SUR to realize the control purposes for its basic motions evaluation. For the designed PID controller, we will present the simulation results and underwater experimental results to evaluate the control effect. Figure 7 shows the PID control scheme for basic motions.

![Fig.7 PID control for horizontal motion](image)

A. Horizontal Motion Control

The horizontal motion experiments combined surge and sway to verify the motion characteristics of the robot in the horizontal plane. The set motion is as follows: 1) surge (move forward along the X-axis); 2) right steering (execute a 90° right turn); 3) sway (move forward along the Y-axis). Figure 8 presents the velocity control of horizontal motion.

![Fig.8 Velocity control of horizontal motion](image)

The experimental results matched the simulated results well during the surge stage, but when the robot rotated, large errors occurred. The reason for this is that we only considered linear and quadratic damping forces in the simulations, whereas in reality, there are other hydrodynamic forces acting on the robot. This is also the disadvantage of the PID control in nonlinear system.

B. Vertical Motion Control

The dynamic feature of the robot in horizontal plane is similar with that in vertical plane. The trajectory we set is as follows: 1) set the topmost point of the hull as the starting point; 2) move downward along the Z-axis for; 3) float upward to the water surface.
Figure 9 shows the velocity control of vertical motion. The experimental results matched the simulated results reasonably well. The maximum errors appeared toward the top of each curve, which represents the deepest position during the experiments. The reasons for the errors is that even though the water pressure variation was considered in the simulations, as the increasing of the depth, the decreasing of the effective propulsive force may not be linearity, which was considered as linear item in the simulation.

V. CONCLUSIONS

The paper focused on control system design for the novel spherical underwater robot. An effective master-slave structure of the control circuit was designed. The master side was to collect the sensor data and realize the control algorithm and communication. The slave side was to control the propulsion system. In order to evaluate the response time and availability of the control system, the horizontal motion and vertical motion control experiment and were carried out. The experimental results showed that the control system and control strategy were available. In the future, a more effective nonlinear control method should be used to realize hybrid motion. We will also consider adjusting the magnitude of the propulsive forces as well as their directions to enhance the control accuracy and stability of the robot.

REFERENCES


