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Electrical System Design of a Spherical Underwater Robot (SUR-II)

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***Abstract*— This paper presents the electrical design for a spherical underwater robot, SUR-II. The master-slave structure control circuit is designed to realize sensor data collection, control algorithm realization, control command transmission, motor actuation and etc. TMS320F28335 and ATMEGA 2560 are used for master and slave processors respectively. Depth sensor and MEMS IMU are employed to realize closed-loop control. To enhance the accuracy of the sensor data, the noise source for sensors is analyzed, and then the sensor data calibration is carried out. To realize communication exactly between the master processor and slave processor, we define a communication law. Only the direction of thrusters is controlled by servomotors to realize underwater motion. In order to evaluate the response time and availability of the control method and electrical system, the depth control experiment and stability experiment are carried out. In these experiments, PD controller is used to control the servomotors. The experimental results show the robot can realize underwater motion just based on controlling the direction of the thruster. The response time is about 40 seconds in the depth control experiment. Because the water resistance is very small in yaw direction, the response time only 10 seconds in the stability experiment.**

Keywords: Electrical system design; spherical underwater robot; sensor data calibration; MEMS IMU

I. INTRODUCTION

In recent years, the applications of autonomous underwater vehicles (AUVs) have been expanded, and now include fields such as ocean research, scientific investigation, ocean development, and underwater projects and etc. 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.

Due to the good water-pressure resistance of spherical objects, spherical robots can realize rotational motion with a 0□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. For the attitude measurement and control, an IMU was employed.

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 located around the equator of its spherical hull. The diameter is only 150 mm and a gyroscope is used to measure the angle in yaw direction. This micro-robot was developed to monitor nuclear storage ponds and wastewater treatment facilities to prevent leakage. Both of these robots used propellers on the outside of their bodies for their propulsion systems. Other spherical underwater robots have used water-jet thrusters. Researchers at Harbin Engineering University developed a spherical underwater robot with three water-jet thrusters [5, 6]. However, the propulsive force of the thrusters was considerably reduced because the water input pipeline was curved. Researchers at the Beijing University of Post and Telecommunications developed a spherical underwater robot with one tunnel propeller [7]. 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 could not carry out other hybrid motions because it only had one propeller.

In our laboratory, we developed a spherical underwater robot (SUR-II) that used three vectored water-jet thrusters for its propulsion system [13–25]. 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 for the SUR-II. The servomotors are employed to change the direction of the water-jet thruster. Each of a thruster owns 2 degree of freedom, so the robot can realize 3D motion by combining the three propulsive forces. In [20], 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 select one of the thruster as the head of the robot. The other 2 provide propulsive force when the robot move in horizontal direction.

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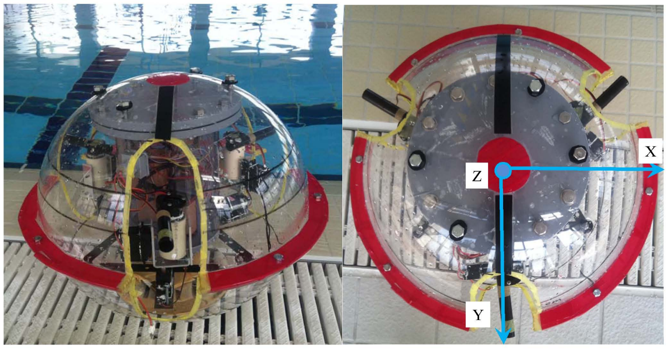


(a) Side view (b) Top view

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

The electrical system is a basic of underwater robot to realize closed-loop control. Processor decides the computational ability of an underwater robot. It is the brain of a robot. A sensor system like the eyes of a robot, it decides the accuracy of motion control. A suitable sensor system is very important for the robot, many issues should be considered, such as cost, volume, accuracy, stability and so on. The propulsion system like legs of a robot. In another word, the processor decides what the robot should do and control the propulsion system to realize underwater tasks, the sensor system feedback what has been done.

The paper is organized as follows: The section II introduced the hardware of the electrical system of the spherical underwater robot. And then in the section III, the software design includes software structure and communication law were introduced in detail. After that some experiments have been carried out in section IV. Finally, the conclusion and future work are listed in section V.

II. Hardware Design

A. Sensors

For a monitoring task, attitude information is so important to the stability of an underwater robot. Gyroscope and compass are the most suitable sensors for the task. Depth sensor and altitude sensor always are employed to get the depth and altitude information. According to the size and manufacturing principle, gyroscope can be broadly divided into 3 categories, machined gyroscope, optic gyroscope, and MEMS gyroscope. In our research, limited by the size of water-proof box and cost, optic gyroscope and machined gyroscope plan are abandoned, replaced by a MEMS IMU, ADIS16365 which is small size and low cost as shown in Fig. 2 (a). The MEMS IMU contain 3 gyroscopes, 3 accelerometers and 3 temperature sensors. The temperature sensor is used for temperature compensation to the gyroscope and accelerometer.

The SUR-II design for shallow water, the water depth is about 10 m. The accuracy of depth sensor will affect location accuracy of the robot. Therefore, the measurement range of depth sensor should suitable for this design requirement. In my research, a high accuracy, small size depth sensor is selected to overcome this task as shown in Fig. 2 (b).

(a) MEMS IMU (b) XP-7001MB depth sensor

Fig. 2. The main sensors

B. Sensor data calibration

In order to reduce the noise for the MEMS IMU sensor, an effective filter should be applied in the data preprocessing. Butterworth filter and Kalman filter are very common methods for data processing. Butterworth filter shows excellent work performance on fixed frequency noise. The Kalman filter is optimal recursive data processing algorithm. Therefore, we select these two filters for data processing. To verify the performance of these two filters, a comparison experiment is carried out. The original data is collected from the IMU sensor and then we use the two kinds of filters process the data respectively. Finally, a comparison result is obtained. In this experiment, the sensor keeps static state and the Z axis shown in Fig. 1 (b) match with heave direction when the data are collected. So sensor just affected by the rotation of the earth and the gravity.

The rotation rate of earth is constant and the value is about 0.04 °/s. For a short time experiment, it can be ignored. The gravity is variable in different latitude and altitude. The relationship between the gravity and latitude is shown in (1) which is D'Alembert's formula [26]. The relationship between altitude and gravity can be calculated by (2). However, due to the robot work in shallow water, the maximum difference altitude is about 10m, and the radius of earth is 6378km. Based on the (2), we can get that the altitude almost has no effect on the gravity. Therefore, the D'Alembert's formula can describe the gravity very well.

$$g(L) = g_0(1 + 0.0052884\sin^2 L - 0.0000059\sin^2 2L) \quad (1)$$

$$g(H) = \frac{g_0 R^2}{(H+R)^2} \quad (2)$$

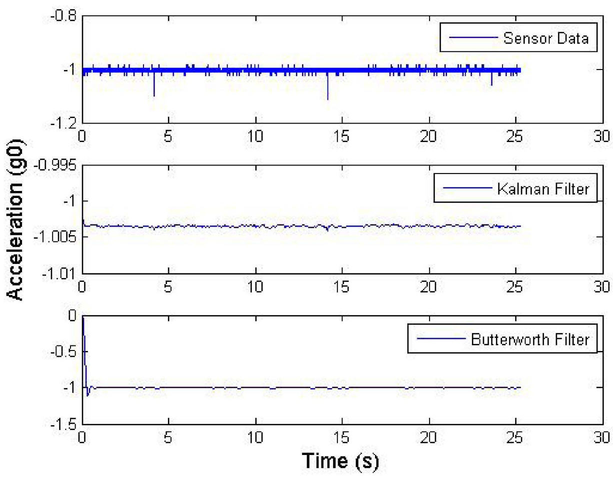
Where, g_0=9. 78049 is standard gravity, L is the latitude, R is the radius of the earth and H is the altitude of experimental field.

B: $E134°03'48.91''$; L: $N34°17'38.50''$; H=22.88m;
Therefore, the gravity for experimental field is g=1.0016g_0.

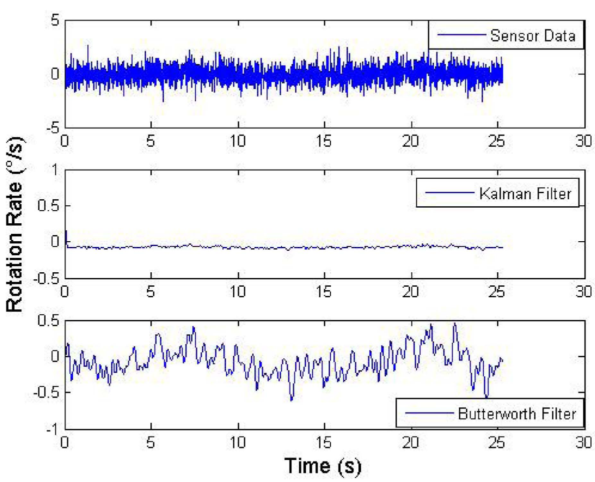
The comparison experimental results are shown in Fig.3. Fig.3. (a) shows the acceleration of Z axis. Because the sensor is static, the value of sensor output should be equal to the acceleration of gravity. The data of sensor exist some noise, after filtering by Kalman filter, the data concentrates on -1.003 g_0, compare with the theoretical value, the error is about 0.1%.

The Butterworth filter also shows a good performance on high frequency noise suppression for the accelerometer. But the Butterworth filter needs a short adjustment time.

The Fig. 3 (b) shows the rotation rate of a gyroscope in the XY plane. Due to Z axis coincide with heave direction, the rotation in XY plane can be defined as yaw motion. The output should be 0 because the sensor is in static state. The noise is big in the sensor original data. The Kalman filter shows a better performance than the Butterworth filter and the data concentrates on 0. In addition, the Kalman filter is a time domain filter. It is easy to realize on the hardware. The Butterworth filter is a frequency domain filter. Therefore, we utilize Kalman filter to the data preprocess.



(a) Acceleration in Z axis



(b) Rotation rate in XY plane

Fig. 3. The comparison results for Kalman filter and Butterworth filter

Compare the results from Kalman filter and Butterworth filter, we can get that the Kalman filter is more efficient than Butterworth filter. We also test the accuracy of depth sensor and get the error between the theoretical value and measured value. The principle of depth sensor is to sense the pressure. So we test the depth sensor under a series of different pressure to simulate difference water depth. The results are shown in Table I.

Because the depth sensor is a high accurate sensor and the error of depth sensor is very small, we just compensate the data of depth sensor by a linear compensation method. After compensating, the measurement error is about 0.5%.

TABLE I. DEPTH SENSOR ACCURACY

Pressure (Kpa)	Depth in theoretical value (cm)	The actual measured value (cm)	Error (cm)
0.00	0.00	0.4	-0.40
25.00	254.93	255.2	-0.27
50.00	509.86	510.4	-0.54
75.00	764.79	765.3	-0.51
100.00	1019.72	1020.2	-0.48
120.00	1223.66	1224.2	-0.54
100.00	1019.72	1020.2	-0.48
75.00	764.79	765.3	-0.51
50.00	509.86	510.3	-0.44
25.00	254.93	255.3	-0.37
0.00	0.00	0.2	-0.20

C. *The actuators*

The robot is actuated by three thrusters. And the direction of the thruster is controlled by two servomotors as shown in Fig. 4.

The features of the actuators are listed in Table II. Based on the two servomotors, the water-jet thruster realized 2 DOF motion.

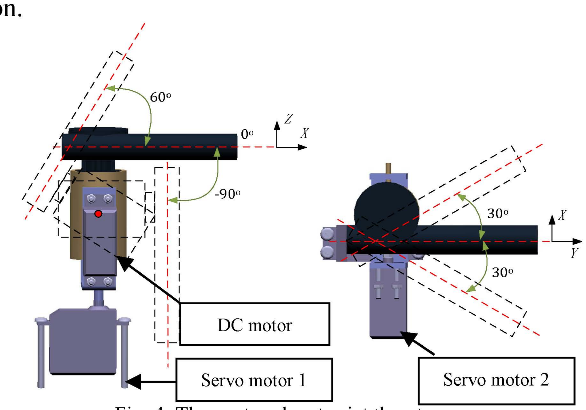


Fig. 4. The vectored water-jet thruster

TABLE II. THE MAIN FEATURE OF THE ACTUATORS

Motors	Motion range (/°)	Max output	DOF
Servomotor 1	-90 ~ +60	12.9N*cm	1
Servomotor 2	-30 ~ +30	12.9N*cm	1
DC motor	-	2N	2

D. *Control circuit design*

The structure of control circuit is designed as a master- slave configuration. The control circuit is divided into master side and slave side. The master side is used for sensor data collection, control algorithm realization and command transmission. The slave side is used to execute the commands from master side and drive the actuators to realize underwater missions. Fig. 4 shows the detail of control circuitry for SUR-II. We also supply the power with two different batteries to reduce the noise from DC motor. The DC motor is used to generate propulsive force, it is the highest energy consumption component in the robot. Therefore, a high-storage battery is applied for three DC motors especially. Of course, this configuration method can prevent mutual interference.

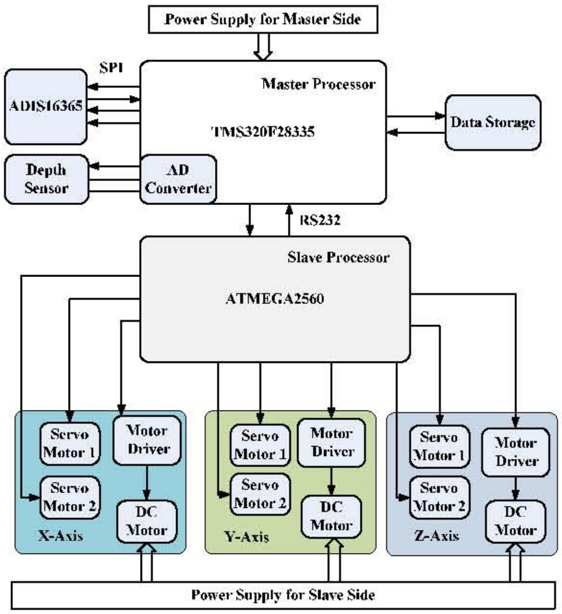


Fig. 5. Block diagram of the SUR-II prototype control circuitry

III. Software Design

There are two methods to control the propulsive force. One is to control the direction of the water-jet thruster. Another is to control the size of the propulsive force. If we only control the propulsive force, the robot cannot realize some hybrid motions. With the vectored water-jet thruster, we used PD controller to control the direction of the thruster and implement some underwater motions. Fig.6 shows the simplified flow chart of the control strategy.

We designed the communication law between the master side and the slave side to prevent communication errors. The detail is shown in table III [27].

TABLE III. The communication law

Start bit	Motor selected	Motor number	Command
53	XX	XX	XX
0	1	2	3
Command	Command	End bits	
XX	XX	50	ff
4	5	6	7

Where bit 0, 7 and 8 is used for checking parity. Bit 1 can decide which kind of motor will be selected; DC motor, servomotor 1 or servomotor 2. Bit 2 can decide which motors will be driven to realize motion. Bit 3, 4 and 5 contain the command to the motors which are selected by bit 2.

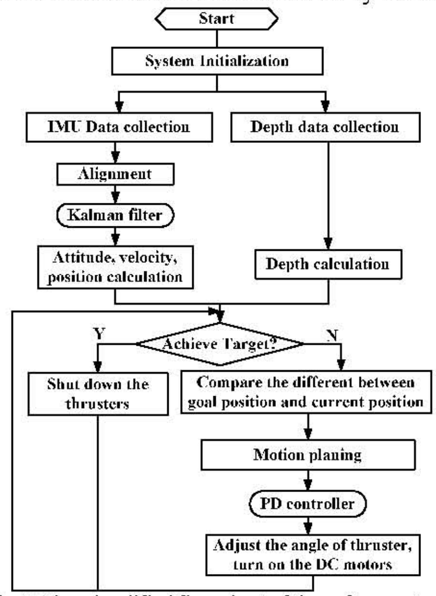


Fig.6. The simplified flow chart of the software structure

IV. Experiments

The propulsive force is too small and the acceleration time is only about 10 second. Therefore, accurate results for speed and velocity are difficult to measure. We only finished the depth control and attitude control for the spherical underwater robot. In these experiments, we just control the direction of thrusters and the propulsive force is still under maximum output [28].

A. Depth control experiment

The depth control experiment is used to verify the accuracy and response time for the SUR-II. The experiment is carried out in a 1.1m pool. The robot needs to complete a task fell to 40cm from the 20cm depth (water surface) and then hold the position at 40mm depth. The depth sensor is installed under the waterproof box. We have adjusted the installation error between the depth sensor and geometric center in control algorithm.

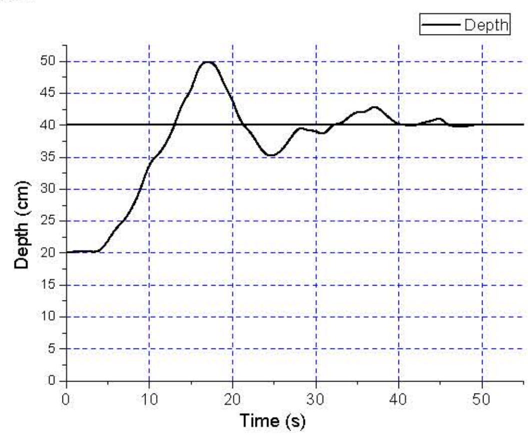


Fig. 7. The experimental result for depth control

In Fig.7, the result of depth control shows that the robot can reach the goal depth after 25 seconds if 5 cm error is tolerable, after 40 seconds, the error less than 2 cm.

B. *Stability in the yaw direction*

Due to the spherical hull, the water resistance is very small in yaw direction. Therefore, the robot is very flexible to adjust the attitude. IMU sensor that has been mentioned in section II is employed to measure the rotational angle. At begin of the experiment, the robot is under stable state. And then, we rotate the robot in yaw direction freely. The sensor detects the angle difference. In order to keep the attitude, the three vectored water-jet thrusters will turn to the opposite direction to generate resisting moment. The robot will turn back to the original direction. 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 torque reduces to 0.

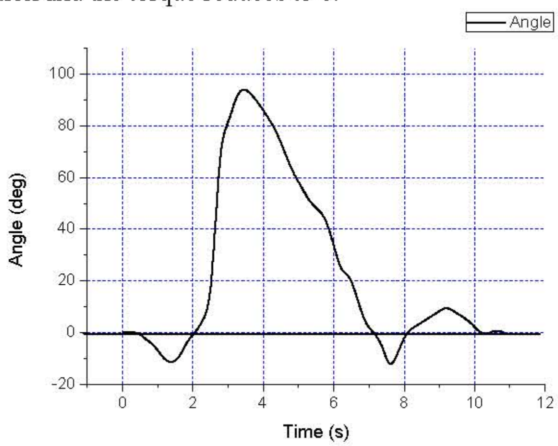


Fig. 7. The experimental result for rotation control

The experimental result shows that the PD controller is available to control some simple motion for the SUR-II. The response time of the robot is just 10 seconds in yaw direction, because the water resistance is very small.

V. CONCLUSION AND FUTURE WORK

In this paper, we focused on electrical system design for the 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. Compared with Butterworth filter, we selected a more efficient filter that was Kalman filter to calibrate the IMU sensor.

In order to evaluate the response time and availability of the control method and electrical system, the depth control experiment and the stability experiment were carried out. In these experiments, we controlled the direction of the thrusters to implement the experiments and PD controller was used to control the servomotors. The experimental results showed that the electrical system and control method were available. The response time was about 40 seconds with high control accuracy in a depth control experiment. The response time was only 10 seconds in stability experiment caused by small water resistance.

In the future, acoustic sensor will be used for underwater positioning to mitigate the limitations of the accelerometer. And a more effective nonlinear control method should be used to realize hybrid motion.

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