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Evaluation of Obstacle Avoidance Performance for Spherical Underwater Robots Using the Ultrasonic Sensor

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Abstract **– Path following with an obstacle execution process is one of the critical capabilities and behaviors of AUV, which is closely related to the safety and execution efficiency of AUVs. Thus, to adapt the assorted underwater environments, and improve the capability of the autonomous obstacle avoidance of underwater robots. In this paper, ultrasonic technology was applied to realize the autonomous obstacle avoidance function of spherical underwater robot (SUR). Firstly, the ranging principle of JSN-SR0T4 ultrasonic sensor module was introduced. Then, the autonomous obstacle avoidance strategy of the SUR was proposed using the ultrasonic module. Finally, in order to validate the effectiveness of the proposed strategy for the SUR, the corresponding simulation and experiments in the real environment were carried out, which verified the feasibility and effectiveness of performing missions.**

Index Terms – Obstacle avoidance, Ultrasonic module, Spherical underwater robot, Control strategy.

I. INTRODUCTION

In recent years, autonomous underwater robots (AUVs) have been widely used in complex underwater environments, such as ocean exploration [1], underwater detection, and rescue, due to the characteristics of wide-ranging operations, flexibility, and strong concealment, etc [2]. In order for AUVs to perform underwater tasks successfully and ensure their own safety, AUVs need to use sensing equipment carried, such as sonar, cameras, ultrasonics, etc., to perceive obstacles in the surrounding environment and achieve real-time obstacle avoidance [3]-[5]. Compared with other sensing devices, ultrasonic sensor is more commonly used recently due to its affordable price and excellent stability [3]. *Bakar et al.* [6] proposes an underwater object detection system using JSN-SR04T that can display measured distances and generate graphs in real time. *Kobayashi et al.* [7] develops a new localization method using ultrasonic sensor for an underwater robot to survey narrow environments based on 3D map-matching. *Salumäe et al.* [8] presents a biomimetic underwater robot U-CAT, which can avoid obstacles near and inside shipwrecks through the equipped eight ultrasonic range finders.

The autonomous obstacle avoidance methods of AUVs, such as artificial potential field (APF) [9], neural network (ANN) [10], map construction, fuzzy logic [3], [11], LOS guidance [12], etc., are commonly used. *Orozco-Rosas et al.* [13] proposed a membrane evolutionary artificial potential field (memEAPF) path planning algorithm considering length, safety and smoothness in complex environments. To reduce the computation time multiprocessors systems is applied, and the effectiveness of proposed algorithm is proved using parallel architectures. *Lin et al.* [14] proposed a recurrent neural network (RNN) for unmanned underwater vehicle to improve the autonomous ability and intelligence of obstacle avoidance planning. *Peng et al.* [15] developed a hybrid algorithm fusing a backstepping technique and a line-of-sight (LOS) guidance principle for path planning of under-actuated autonomous robot. The above algorithms mainly focus on simulation, and lack the consideration of robot model and dynamic parameters.

Besides the above control algorithms, some sensor tools are also used to perform underwater missions [16]. For instance, *Hou et al.* [17] proposed an improved model predictive controller (MPC) to achieve trajectory tracking of biomimetic sphere robot, a global camera system is built to detect surrounding environment. *Li et al.* [3], [18] proposed the path planning method using fuzzy control, which incorporates multi-sensor technology to guide AUVs in complex and unknown environment. *An et al.* [4], [19] proposed an improved Ant Colony Optimization (ACO) algorithm for spherical underwater robot to achieve global path planning. The open MV camera and IMU are combined to perceive the obstacles information and localization for SUR. The above algorithms conducted the simulation and experimental evaluation to verify the performance of proposed control method, but lack of considering the correctness of robot modelling. For micro underwater robots, camera and ultrasonic sensor are widely used due to the features of high-accuracy and small-size [20]-[21]. Moreover, compared with cameras, ultrasonic sensors are more suitable for underwater unknown and turbid environments, which can avoid obstacles in real time and ensure that AUVs can perform missions safely.

Motived by the above consideration, this paper mainly focuses on addressing the obstacle avoidance problem of the spherical underwater robot (SUR) within obstacles environment. The ultrasonic module is used to avoid obstacles in real time. The obstacle avoidance strategy is developed for

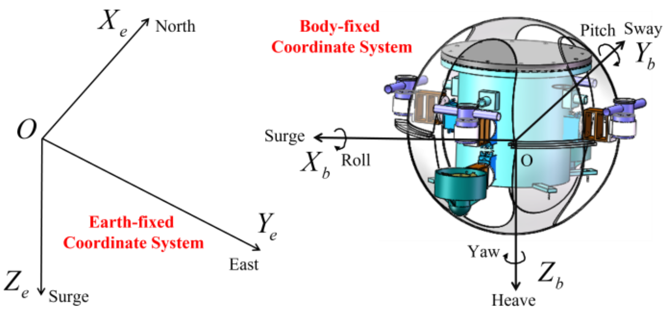

Fig. 1 The coordinate frames of the SUR we designed.

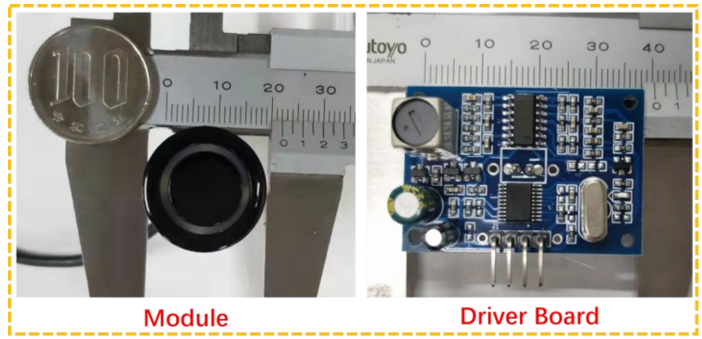

Fig. 2 The ultrasonic module and drive board of JSN-SR0T4.

the SUR. Under the strategy, SUR can follow the reference path and auto-avoid obstacles.

This paper is organized as follows: The prototype of SUR and the features of ultrasonic module JSN-SR0T4 are introduced in Section II. Then, in Section III, an obstacle avoidance strategy is proposed for SUR to avoid obstacles in real-time. The main work of the Section IV carries out the simulation experiments using Webots, which simulates obstacle avoidance capability realistically. Next, experiments in real environment are carried out to validate the effectiveness and practicality of proposed strategy. Finally, Section VI introduces conclusions and future work.

II. Related Work

A. *Previous research of the SUR*

In our previous research, a spherical underwater robot (SUR) is designed with multiple vectored thrusters, as shown in TABLE I. The structure of the SUR is symmetrical to facilitate underwater control. In [22]-[26], a SUR with vectored water-jet thrusters is designed, and the estimated parameters and hydrodynamic analysis are carried out. In [27]-[28], a hybrid propulsion device is proposed for SUR with four vectored water-jet thrusters and two propellers, which has advantages of low-noise and high speed to improve the working efficiency of underwater missions. And the acoustic communication and multi-mode switching methods are also developed for SUR which enhance the feasibility and stability of robot's locomotion.

TABLE I
Previous Research of the SUR

Contributions / Authors	Developed SURs: Thrusters	Developed SURs: Main work
Lin et al (2013) [19]	√ Water jet-based √ Three propellers	3D Model building
Yue et al (2013, 2015) [20]-[21]	√ Water jet-based √ Three propellers	Hydrodynamic analysis Mechantronic system
Li et al (2015, 2017) [22]-[23]	√ Water jet-based √ Four propellers	Kinematics simulation Element analysis
Gu et al (2017, 2020) [24]-[25]	√ Water-jet thrusters √ Hybrid thrusters √ Four propellers	Hydrodynamic analysis Fluid simulation
An et al (2020, 2021) [2], [4], [16]	√ Water-jet thrusters √ Four propellers	Multi-robot Task planning
Li et al (2022)	√ Water-jet thrusters √ Hybrid thrusters √ Four propellers	Multi-mode switching Path following

In the above research, we obtain the hydrodynamic parameters of the SUR, including drag coefficient, viscous coefficient and so on. The coordinate frames of the SUR are shown in Fig. 1.

The kinematic and kinetic model of the SUR can be written as [29]-[31]:

$$\dot{\eta} = J(\eta)v \tag{1}$$

$$M\dot{v} + C(v)v + D(v)v + g(\eta) = \tau \tag{2}$$

where η is the position and orientation of SUR, v is the linear and angular velocities, J is the transformation matrix; And M, C, D, g and τ represents the inertia matrix, Coriolis-centripetal matrix, damping matrix, forces and moments, and forces and moments acting on the SUR, respectively.

TABLE II
Characteristics of the Ultrasonic Module JSN-SR0T4

Items	Characteristics
Size	L 41 x W 28.5 x H 12 mm
Working current	30 mA
Working voltage	DC 5V
Probe frequency	40 KHz
Resolution	About 5 mm
Angle	< 50°
Working Temperature	-10 ℃ ~ 70 ℃
Detecting range	20 cm ~ 450 cm

B. *The ultrasonic module JSN-SR0T4*

The ultrasonic module JSN-SR0T4 is used in this paper, which is widely used for ranging and autonomous control in complex, underwater environments due to its waterproof, small size, high precision, anti-jamming, etc. The ultrasonic module and drive board of JSN-SR0T4 is shown in Fig. 2. The characteristic of the module is described in TABLE II.

Working principle of the ultrasonic module: The module triggers measurement distance using the IO port and supplies a high-level signal of at least 10 µs. Simultaneously, the internal integrated module automatically transmits 8 square-wave waves of 40 KHz, and then automatically detects whether there is a return signal. If a signal is returned, the ECHO output of the IO port will be high level, and the high time refers to the time from transmit to return. Finally, total time is used to calculate distance, and continuous cycle measurement is used during SUR's locomotion to detect obstacles in real time.

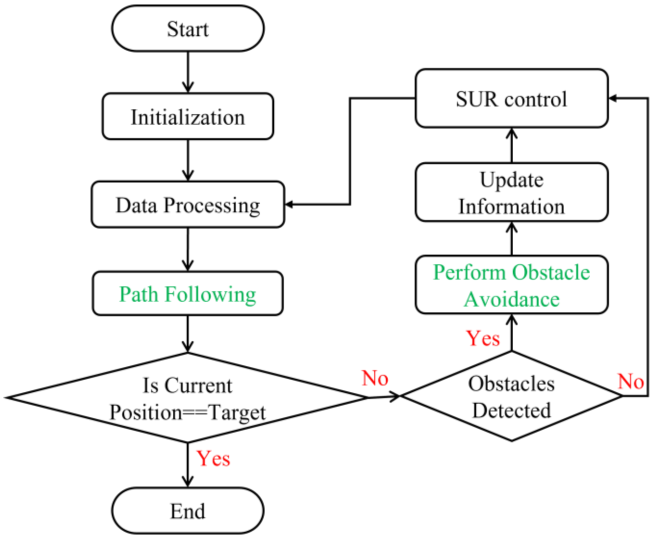

Fig. 3 The obstacle avoidance strategy proposed for the SUR.

In this paper, the main controller uses AT Mega 2560 (Arduino, Italy). After the ultrasonic module data is collected, the obstacle avoidance is completed after preprocessing. In the process of path tracking, we use the path point to track desired trajectory, the target position is known, and the tracking and obstacle avoidance are realized by continuously updating the information of the position and distance. In future work, we will complete multi-objective coordinated motion to improve efficiency.

III. Obstacle Avoidance Strategy

In this section, in order to improve the obstacle avoidance capability of the SUR, an autonomous obstacle avoidance strategy is proposed considering the characteristics of ultrasonic module JSN-SR0T4.

Obstacle avoidance strategy for SUR is urgently needed, due to the obstacle cannot communicate with AUVs. When obstacles are detected, SUR avoid obstacles using ultrasonic sensor, as shown in Fig. 3. The obstacle avoidance strategy is as follows:

During the execution of missions, the SUR moves along the desired trajectory, and then uses the ultrasonic sensor to perceive the surrounding environment. When an obstacle is detected, the obstacle avoidance strategy is activated. After avoiding obstacles, the SUR will follow the desired trajectory until reaching the target position.

Supposing the mission variable is defined as P, which satisfies:

$$P = f(\eta) \tag{3}$$

Then, the derivation of P yields:

$$P' = {f(\eta)}/{\eta} = J(\eta)v_R \tag{4}$$

where v_R is the velocity matrix of SUR.

During the execution of missions, the relationship between the SUR and the obstacles yields:

$$D = \sqrt{(x_O - x_b)^2 + (y_O - y_b)^2} \tag{5}$$

When SUR encounter the obstacle, the avoidance velocity v_R, which is a variable, must be greater than the velocity v_O of the obstacle.

The angle ψ at the next moment is updated as:

$$\psi = \alpha \pm \left(\frac{\pi}{2} - \arctan\frac{l_d + \delta}{k(D - l_d)}\right) \tag{6}$$

where α is the angle between the SUR and obstacle position, l_d is the shortest distance, the variable δ is used to ensure the safety of the SUR, k is the convergence coefficient. Noted that the plus and minus signs depend on the location of the obstacle, if the obstacle is at [0 180°], belong to the plus sign. Conversely, belong to the minus sign.

IV. Simulation Results

In order to verify the effectiveness of the proposed control strategy, we conducted the obstacle avoidance experiments in Webots. It can realistically simulate the movement of the SUR in the 3D virtual world, and the robot model and physical characteristics, such as mass, joints, friction coefficient, etc., can be constructed realistically. Firstly, the rectangular water tank is built, and then imported the model of the SUR. Next, a controller is developed to verify the performance of the proposed obstacle avoidance strategy and improve the working efficiency of the SUR. In real environment, the ultrasonic module JSN-SR0T4 is used, to simulate the SUR obstacle avoidance performance realistically, we add sensor to the robot body, and then configure it according to the characteristics of ultrasonic features (in Table II).

In the simulation experiments, three static obstacles are placed on the reference path. The pool is built with the length of 10 m, the width of 5 m, and the depth of 5 m. The positions of the three obstacles are x_{O1}=*2.0 m*, y_{O1}= *1.2 m*, x_{O2}=*4.5 m*, y_{O2}=*2.5 m*, x_{O3}= *8.0 m*, y_{O3}=*4.0 m*. The size of the obstacle is 1.6 m × 0.3 m × 0.8 m (length × width × depth), and the distance from the center of the obstacle to the horizontal plane is -0.15 m.

The motion process of the SUR following the reference path is shown in Fig. 4. SUR starts from starting position *(0.5 m, 4.5 m)*. The first obstacle was detected at about 4 s. After avoiding the obstacle, it then continues to follow the reference path. When the second obstacle is detected, at about 18 s, the SUR avoids the obstacle again and then follows the path. After avoiding the third obstacle, the SUR will move towards the target position for a total of 45 s. It can be seen that SUR can successfully avoid obstacles and reach the target position.

The tracking trajectory of the SUR is shown in Fig. 5. It can be seen that the motion trajectory of SUR is smooth and there is no large jitter phenomenon, which further validates the effectiveness and stability of the proposed obstacle avoidance strategy.

V. Experimental Results

After completing the simulation tests, in order to further

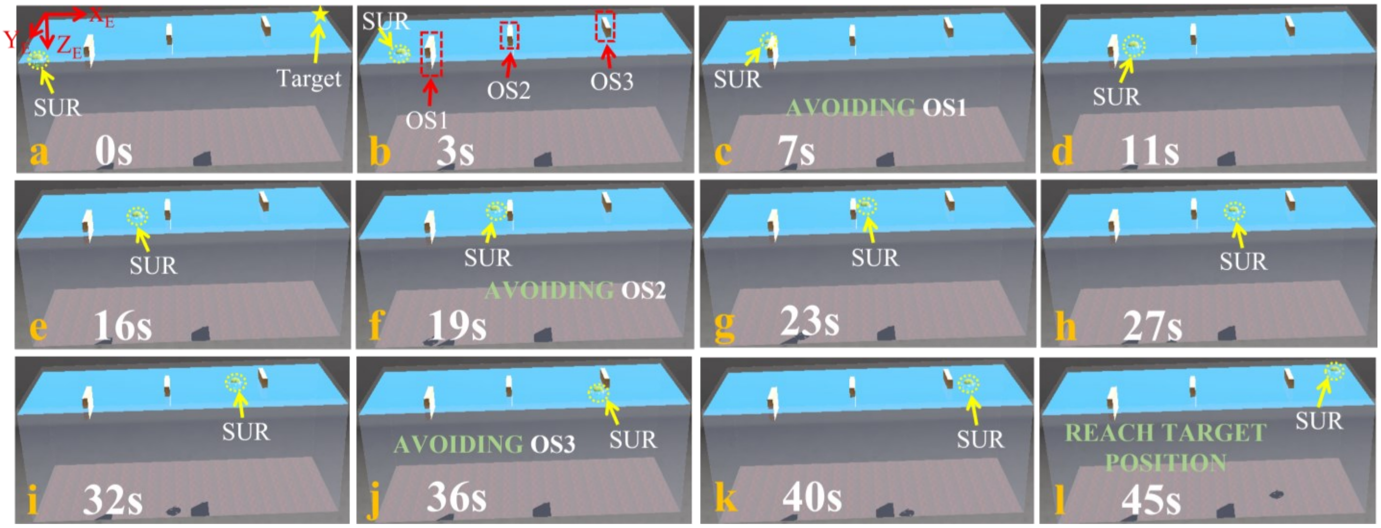

Fig. 4 The trajectory tracking progress of the SUR in presence of multi-obstacle environment (in simulation).

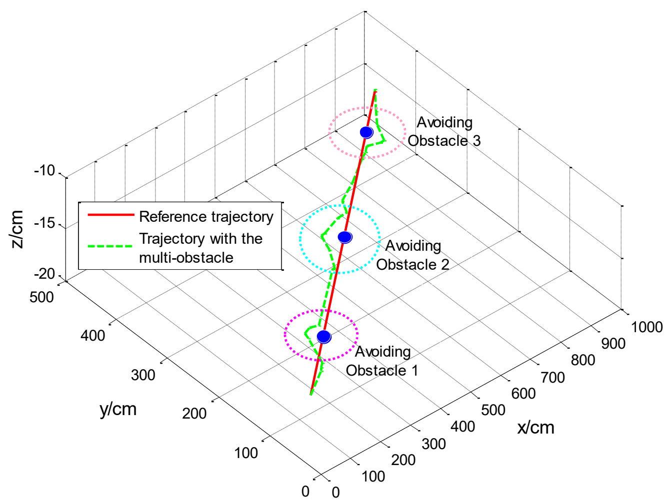

Fig. 5 Trajectory tracking result of SUR under multi-obstacle.

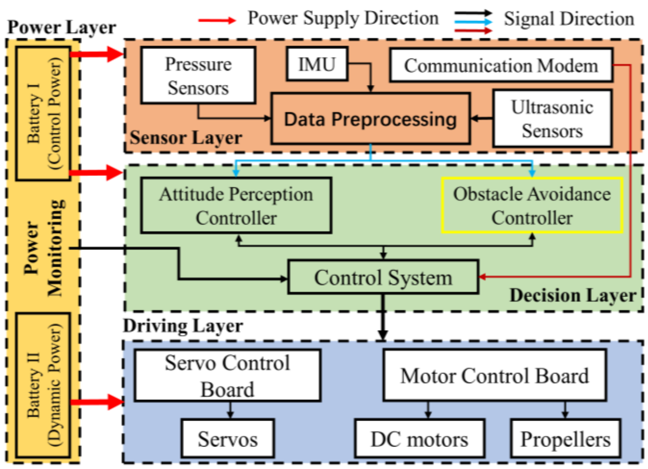

Fig. 6 The control system of the SUR.

verify the proposed obstacle avoidance strategy, the experiments in the real environment are carried out. The tracking trajectory experiments in presence of single-obstacle and multi-obstacle were performed, respectively. Noted that in the multi-obstacle experiments, only two obstacles are set on

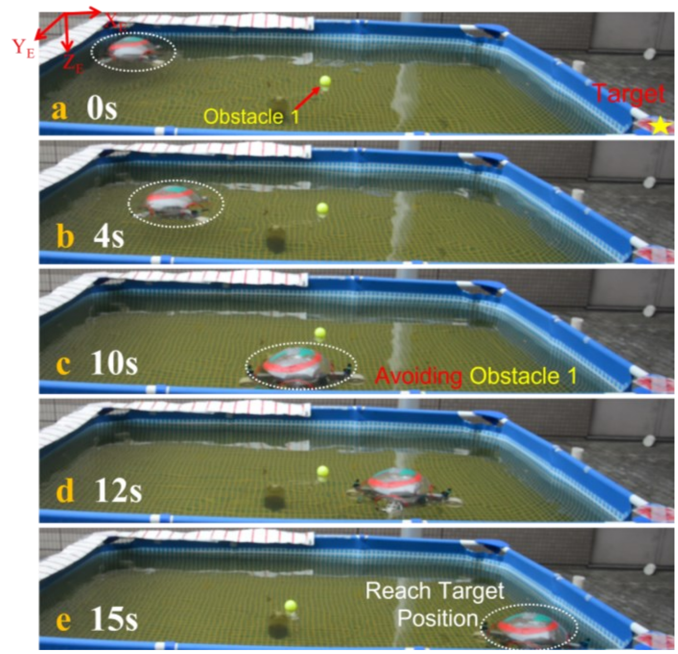

Fig. 7 Trajectory tracking process of SUR under single-obstacle.

the reference path due to limit of the size of the experimental pool.

To improve the working efficiency of the controller, the control system is divided into four parts: power layer, sensor layer, decision layer and driving layer, as shown in Fig. 6. The controller ATMega2560 is employed to communicate with sensor layer, which can obtain the information of surrounding environment. After the SUR processes the signal, it feedbacks signal to the driving layer to adjust the robot locomotion and attitude in time.

Then, the single-obstacle experiments are carried out to further validate the effectiveness of the obstacle avoidance strategy. The trajectory tracking process of the SUR is shown in Fig. 7. The SUR starts from the starting position (see Fig. 7 a), avoids obstacle at about 4 s. The obstacle is placed at position *(1.5 m, 1.0 m)*. After avoiding the obstacle, the SUR

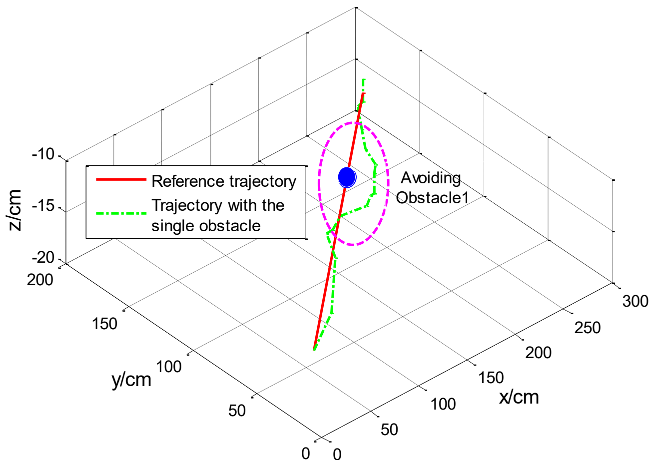

Fig. 8 Trajectory tracking result of SUR under single-obstacle.

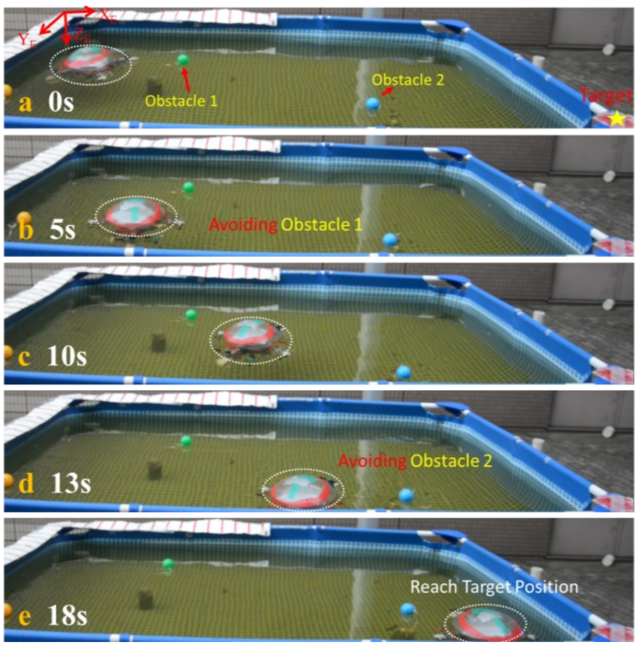

Fig. 9 Trajectory tracking process of SUR under multi-obstacle.

track the reference path until it reaches the target position *(2.75 m, 1.75 m)*.

The tracking trajectory curve of SUR is shown in Fig. 8. As can be seen that SUR can safely pass obstacles, and the total tracking time is about 15 s.

Next, to further verify the effectiveness of the proposed strategy, the multi-obstacle experiments are carried out. The trajectory tracking process in presence of multi-obstacle is shown in Fig. 9. The SUR starts from the starting position *(0.25 m, 0.25 m)* (see Fig. 9 a), avoids the first obstacle at about 2 s. The obstacles are placed at position *(0.6 m, 0.5 m)*, *(2.0 m, 1.4 m)*, *respectively*. After avoiding the first obstacle, the SUR track the reference path again, at about 5 s. The target position is consistent with that in the single-obstacle experiments. At about 18 s, the SUR reached the target position. It also can be seen from Fig. 10 that the tracking curve of the SUR is smooth. the SUR can successfully avoid obstacles and reach the target position, which verify the effectiveness and practicality of the proposed control strategy.

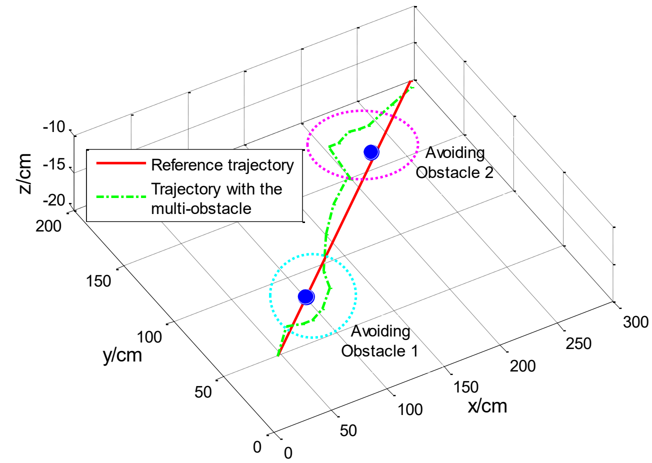

Fig. 10 Trajectory tracking result of SUR under multi-obstacle (in real environment).

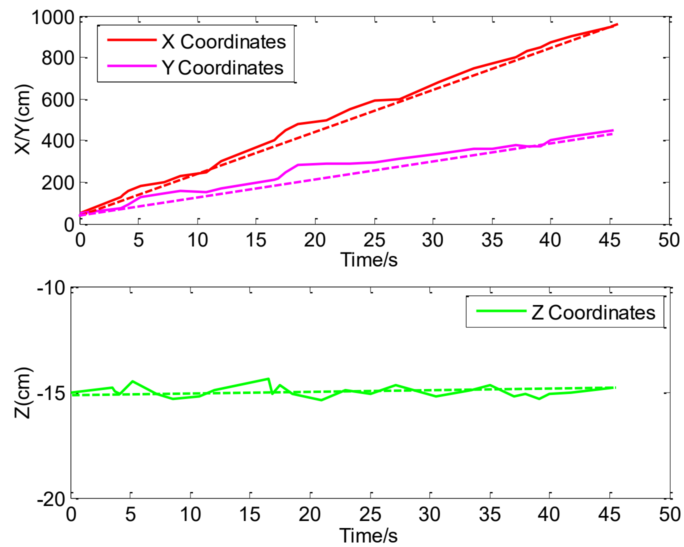

Fig. 11 Trajectory tracking error analysis of the simulation (see Fig. 5).

According to the simulation and experimental results, we carried out the error analysis of the abscissa and ordinate, as shown in Fig. 11. Taking the simulation as an example (see Fig. 5), it can be seen that compared with the desired trajectory (dotted line), the horizontal and vertical coordinate errors are stable within 3 cm. In real experiments, the error is calculated about 5 cm, which further verifies the effectiveness of the proposed obstacle avoidance strategy. Due to the existence of water waves and external interference in the real environment, the error will be larger than that of simulation, but it can guarantee perform tasks safely.

V. Conclusions

To improve the working efficiency and enhance adaptability in unknown environment of the spherical underwater robot, this paper proposed an obstacle avoidance strategy for the SUR using ultrasonic module JSN-SR0T4. The characteristics of the ultrasonic module were introduced, and the detecting accuracy was tested. Then, according to its characteristic analysis the autonomous obstacle avoidance strategy is proposed for prototype of SUR. Next, a series of obstacle avoidance experiments were performed using Webots in the presence of static obstacles, which realistically simulate the obstacle avoidance performance of the SUR we designed. Finally, to further verify the performance of the proposed strategy, the SUR was assembled, and obstacle avoidance experiments in real environment were performed. The experimental results validated the effectiveness and flexibility of its real-time obstacle avoidance. In the future, we will use multi-sensor fusion technology to conduct experiments in the lake to verify obstacle avoidance performance.

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