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Turning Locomotion Analysis and Performance Evaluation for a Spherical Underwater Robot

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***Abstract* – Although the spherical underwater robot has the advantage of 0 radius for the turning locomotion, a variable radius of turning locomotion is also necessary for the path planning and obstacle avoidance of an underwater robot. This paper focused on the turning locomotion with variable radius for the forth-generation spherical underwater robot (SUR IV) with the hybrid propulsion device. The hybrid propulsion device could be controlled by PWM signals to modify the thrust and linear velocity. The motion state of the turning locomotion was developed in different radius. The centripetal force of curve motion is also analyzed by Newton's first law. The relationship between the centripetal force and turning radius was proposed. In order to verify the turning locomotion with different turning radius, the experiment was carried out in the swimming pool. The experimental results show that the change of the turning radius can be achieved by adjusting the control input PWM signal of the main thruster and the assist thruster.**

Index Terms* – *Spherical underwater robot, Turning locomotion, Centripetal force, PWM signal, Radius of curvature

I. INTRODUCTION

Autonomous Underwater Vehicles (AUVs) are widely employed in the underwater environment and played an important role in ocean exploration and discovery research [1]-[2]. The different applied situation will be matched to different mechanical structure, measurement, movement dimension, control methods or figure of the AUVs. For instance, a small scale, single-jet underwater robot may be available for the purpose of easily enter and move in some narrow places or tubes underwater [3]. Another ball-shaped underwater robot which equipped with one pump and two valves is specifically presented for the direct visual inspection for the inside of nuclear powerplants [4]. The streamlined shapes can make the robot move in a high speed underwater especially for the big scale robot [5]. Some underwater robots are imitated from the underwater creatures as fish or shrimp are required for actuating flexible movements [6]-[7]. Amphibious robots which can walk on land and swim in the water is designed to be used in different environments [8]-[10]. It is well known that the propulsion devices always play a vital role in underwater robots because it can determine the motion dimension, mode and speed of the robot. Researchers in the University of Florence developed a novel underwater robot named as "Tifone". For the expected performances and requirements, the main focus of this research is related to its propulsion device [11]. Various designs for the propulsion device are presented for the AUVs, thrusters as propellers, water-jet, valves and pumps are realized in different underwater robots [12]-[15]. In some special tasks, such as path planning, obstacle avoidance, etc., underwater robots are also required to have multiple degrees of freedom, good stability and flexible swimming work [16]. The good stability of the robot is extremely important for it to complete the task underwater [17]-[18]. Researchers in Michigan Technological University presented a roll mechanism and control strategy for AUVs. And some experiments were conducted to discuss the high efficiency of the controller on turning motion [19]. In the study of our previous research, a Spherical Underwater Robot (SUR) was presented with multi-vectored water-jet thrusters [20]. The simulation and experiments for the thrusters were verified the performance of an SUR prototype [21]. Based on these mentioned researches, Yue et al. proposed the second-generation Spherical Underwater Robot (SUR-II) [22] with the Computational Fluid Dynamic (CFD) simulation to calculation the relationship between the drag coefficient and the Reynolds number [23]-[25]. In addition, the propulsion force of the single water-jet thruster measured from the experiments by using load cell [22]. The hardware design and control circuit of the SUR were also enhanced for the further research [26]. For the further development, a father-son underwater intervention robotic system was established with SUR II and IPMC microrobot to achieve as the underwater manipulation in complex situation [27]-[28]. The third-generation Spherical Underwater Robot (SUR III) was designed by Li et al. Researches as [29]-[32] proposed a prototype SUR with four water-jet thrusters. Gu et al. continued to analyze and appraise the characteristic of the SUR III by carrying out experiments with propulsion sysem[33]-[34]. And the underwater acoustic communication system was also proposed for the SUR [35]-[36]. These underwater vehicles will supply advantages such as moving in a narrow space, fast cruising, amphibious movements on land and in the water. Therefore, a multi-mode of high and low speed for an underwater propulsion system is need to be proposed urgently during ocean inspections. On this basis, a novel spherical underwater robot is developed with the hybrid propulsion system including both water-jet thrusters and propellers. This SUR can be allowed flexibly underwater.

This paper mainly described the turning locomotion of the forth generation Spherical Underwater Robot (SUR IV). Primarily, the hybrid propulsion device will be proposed in the section II, and the motion state of the turning locomotion in anticlockwise and clockwise is also achieved. According to Newton's first law the relationship between the centripetal force and turning radius is calculated in the section III. Using the PWM signals to control the DC motors of the thrusters is an important method to achieve the various radius. In order to confirm the performance of the various radius turning locomotion, experiments as turning locomotion were carried out in the swimming pool. Experimental results indicated that the variable PWM signal is achievable for varying the turning radius.

II. PROPULSION DEVICE FOR SUR IV

A. *The Hybrid propulsion device of SUR IV*

For the novel spherical underwater robot, a hybrid propulsion device is employed as the main power. The hybrid propulsion device includes both propeller and water-jet thruster as illustrated in Fig. 1. Due to the good power management and reliability, the propeller is often used for the underwater robot. The water-jet thruster has the good performance of low noise. For ease of control, the same DC motors are used for both propeller and water-jet thruster. The thrust direction of the propeller and water-jet thruster is adjusted by a servo motor with a range of 0-180 degrees. The DC motors can be reversed, in fact, the thrust direction can vary between 0 to 360 degrees.

B. *Motion state on XY plane*

For an underwater robot, there are 6 Degrees of Freedom (DoF) as surge, sway, heave, roll, pitch and yaw. In different research, sometimes DoF as sway, roll and pitch will be rarely employed for an underwater robot, but these degrees of freedom also perform a crucial duty in some specific research. The focus of this paper is to study the turning locomotion of the robot on the XY plane which is the combination of two degrees of freedom with surge and sway. In the experiment, the robot can float on the water, so the buoyant and gravity are not considered in this paper. Fig. 2(a) illustrates the forward motion in surge for the SUR IV. At this point, the two opposite thrusters need to provide an equal thrust to ensure that the robot is traveling straight. When one of these two thrusters is reversed, the robot will rotate around its center of gravity. These two kinds of motions can actually be considered as the two extreme states of the radius of curvature. Although spherical robots have the characteristics of zero turning radius, in practical applications such as path planning obstacle avoidance, a proper radius of turning locomotion is also necessary.

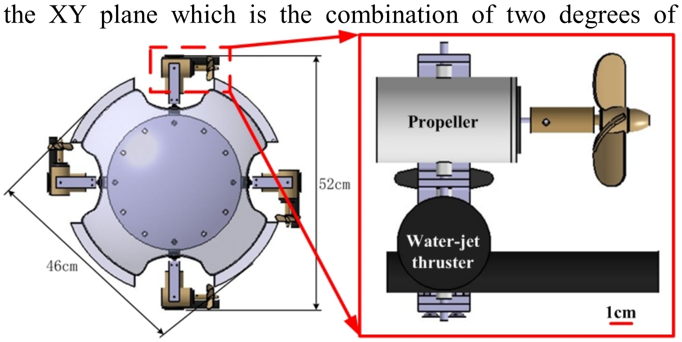
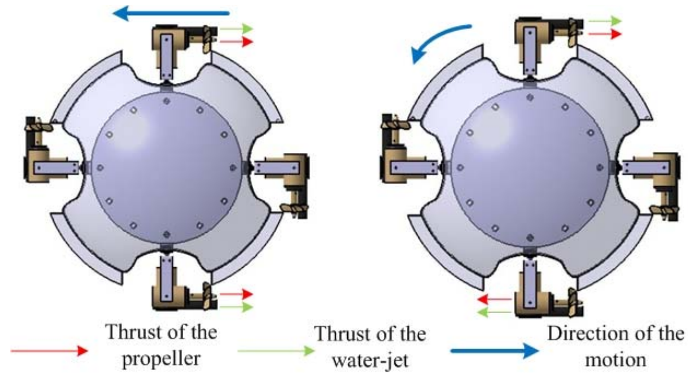


Fig. 1 The hybrid thruster for SUR IV



(a) Forward motion (b) Rotation motion

Fig. 2 Motion state in XY plane

In order to achieve different turning radius in the turning locomotion, the two opposite thrusters are divided into a main thruster and an assist thruster. The input PWM signal of the main thruster is fixed in this paper, and the input PWM signal of the assist thruster will be modified for different centripetal force. The direction of the turning locomotion is the same as the direction of the assist thruster. Fig. 3 shows the different radius of the turning locomotion by adjusting the PWM signals of main thruster and assist thruster.

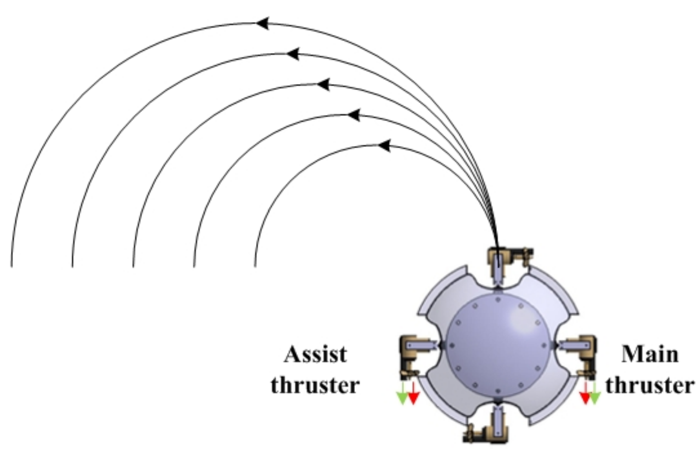


Fig. 3 Turning locomotion in different radius

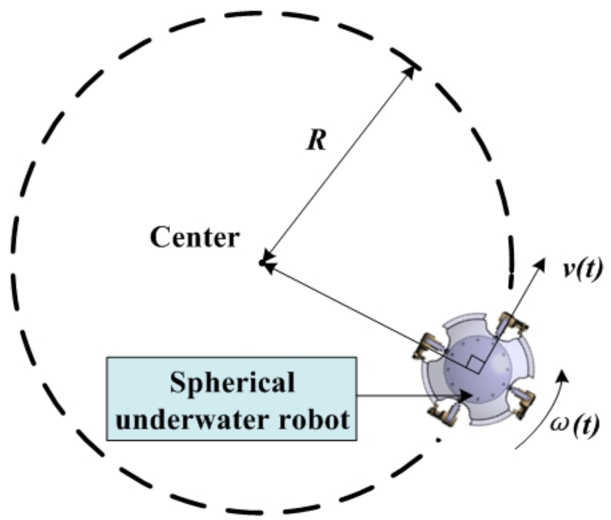


Fig. 4 Turning locomotion model for SUR IV

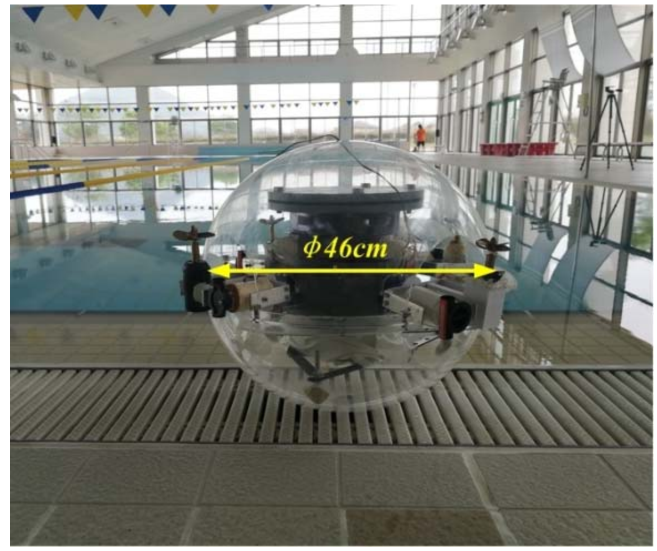


Fig. 5 The prototype of the SUR IV

III Turning locomotion analysis

When underwater robots make a turning locomotion, a radius Fig. 4 Dynamic analysis of SUR IV for circular motion of curvature is generated. Here is the circular motion as an example shown in Fig. 4. According to Newton's first law, the relationship between the radius of curvature and the centripetal force when the rigid body is moving in a uniform circular motion can be explained in equation (1),

$$F_{CF} = m\omega(t)^2 R \tag{1}$$

where the F_{CF} is the centripetal force of the underwater robot, m is the mass of the robot underwater, $\omega(t)$ is the angle velocity of the robot underwater and R is the radius of curvature. The relationship between centripetal force and linear velocity can be replaced according to equation $\omega(t)=\frac{v(t)}{R}$. Here is the equation (2),

$$F_{CF} = \frac{mv(t)^2}{R} \tag{2}$$

It can be informed from the equation (2) that when the centripetal force and the linear velocity change, the radius of curvature changes. For the SUR IV, the centripetal force can be adjusted by modifying the PWM signal of the two opposite thrusters, and the linear velocity is also adjusted in this process.

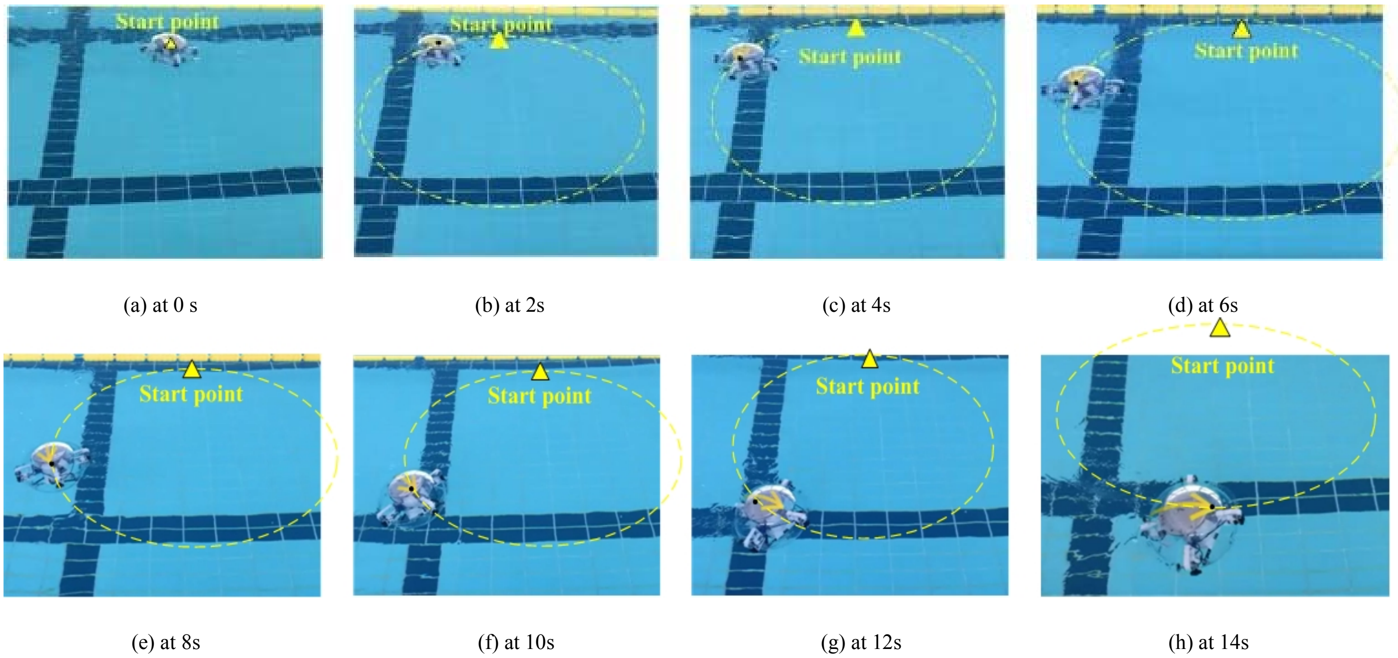
IV Experiments and Results

In order to verify the turning locomotion performance of the SUR IV. Some experiments are conducted in the swimming pool. The SUR IV which is employed in these experiments is shown in Fig. 5. The swimming pool is 25 meters in length, 11meters in width and 1.1 meters in depth. The experiments include both anticlockwise and clockwise turning locomotion o as the range of 0 to 180 degree. The PWM signals for the master thrusters are set as 100% duty cycle to ensure the enough power for the robot. And the assist thrusters are set a various PWM signals with a range of 80-95% duty cycle for anticlockwise and 70-90% for clockwise.

Fig. 6 gives the process of the anticlockwise turning locomotion. The motion trajectory can be fitted to a curve as shown in Fig. 6. From the start point to the end the robot completes a 180 degree turn at a variable radius of curvature. The max radius is 125cm in this experiment, and at this point the PWM signal is at 75% duty cycle. Another experiment is the clockwise turning locomotion as shown in Fig. 7. Because the difference of the duty cycle, the period of the turning locomotion for clockwise is faster than anticlockwise. And the turning radius is smaller too.

V Conclusion

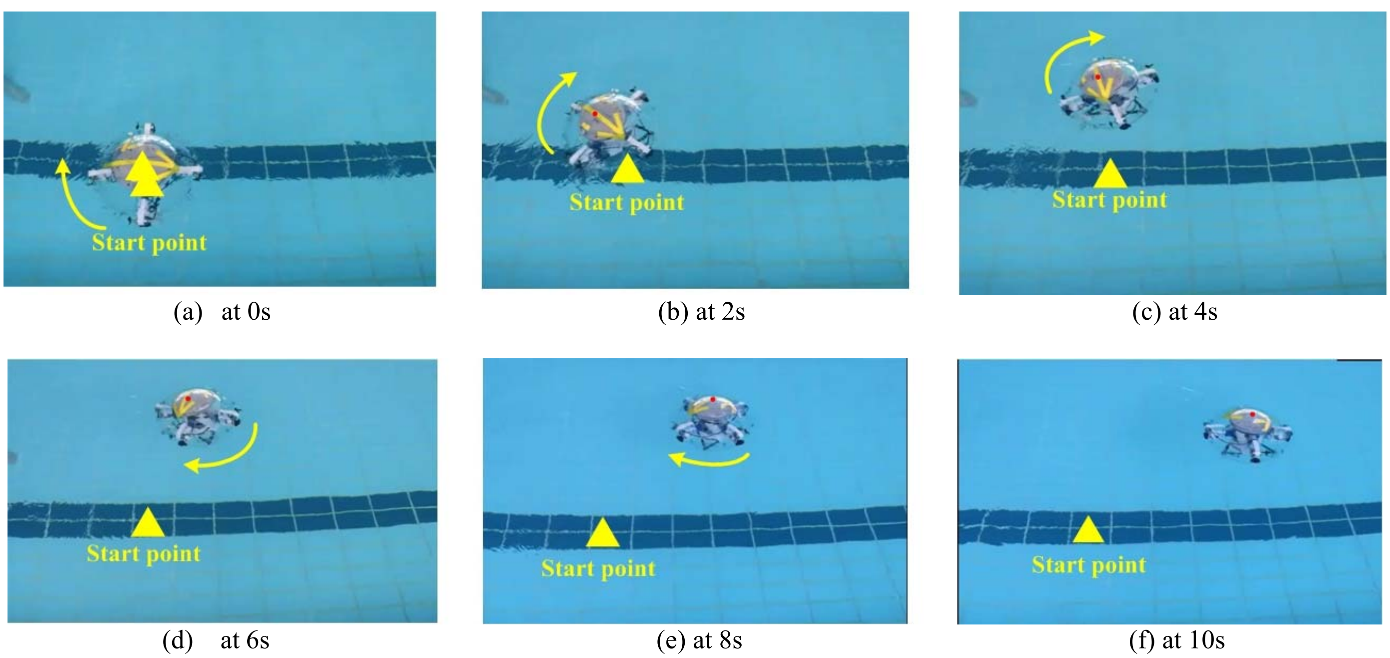
In this paper, it is presented the turning locomotion of a spherical underwater robot with the hybrid propulsion device. Although the spherical underwater robot has the advantage of 0 radius for the turning locomotion, a variable radius of turning locomotion is also necessary for the path planning and obstacle avoidance of an underwater robot. This paper focused on the turning locomotion with variable radius for the forth-generation spherical underwater robot (SUR IV) with the hybrid propulsion device. The hybrid propulsion device could be controlled by PWM signals to modify the thrust and linear velocity. The motion state of the turning locomotion was developed in different radius. The centripetal force of curve motion is also analyzed by Newton's first law. The relationship between the centripetal force and turning radius was proposed. In order to verify the turning locomotion with different turning



(a) at 0 s (b) at 2s (c) at 4s (d) at 6s

(e) at 8s (f) at 10s (g) at 12s (h) at 14s

Fig. 6 Anticlockwise turning locomotion for SURIV



(a) at 0s (b) at 2s (c) at 4s

(d) at 6s (e) at 8s (f) at 10s

Fig.7 Clockwise turning locomotion for SURIV

radius, the experiment was carried out in the swimming pool. The experimental results show that the change of the turning radius can be achieved by adjusting the control input PWM signal of the main thruster and the assist thruster. In the future, we will focus on the relationship between the PWM signals and the radius of the curvature by the experiments.

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