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Underwater Performance Evaluation of an Amphibious Spherical Mother Robot

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***Abstract*–Various underwater microrobots were applied widely to underwater operations in narrow spaces in recent years. By having the compact structure, the robots had some limitations in locomotion velocity and enduring time. Hence, a mother-son robot cooperation system was proposed to solve these limitations. A novel amphibious spherical robot was designed as the mother robot to carry the microrobots as son robots for collaboration. The spherical mother robot consisted of a sealed hemispheroid, two openable quarter spherical shells, a plastic circular plate, a plastic shelf for carrying microrobots and four actuating units. Each unit was composed of a water jet propeller and two servo motors, each of which could rotate 90° in horizontal or vertical direction respectively. The robot could implement on-land locomotion, as well as underwater locomotion. In this paper, we developed the prototype mother robot and did the force analysis of the actuating system in horizontal direction and vertical direction. And plenty of underwater experiments of the robot in the semi-submerged state were conducted to evaluate the underwater performance, including the moving forward experiments in the moving forward experiments of the robot actuated by two main actuating units and four actuating units. From the results of the underwater experiments, we got a maximal moving forward velocity of 13.7 cm/s under the efficient actuating and a maximal rotating velocity of 64.3º /s under a duty of 100%.**

Index Terms – Spherical robot, Amphibious robot, Water-jet propeller, Mother robot.

I. INTRODUCTION

Underwater robots have been widely used in submarine topography survey, pipeline cleaning, water samples collection, and recovering underwater objects for several years. However, it is hard for normal underwater robots to do operations in limited spaces. For having the compact structure, microrobots actuated by smart actuators including ICPF actuators [1]-[7] and SMA actuators [8]-[10] are utilized to work in narrow spaces. Nevertheless, the compact structure also brings limited multi-functionality, locomotion velocity and enduring time to microrobots. Microrobots usually have a lower speed because of the properties of the smart actuators. And it is difficult for the wireless microrobots to achieve a long enduring time by a compact structure, with which the robot is unable to carry large power supply. For wire microrobots, they can get enough energy supply from power supply through the cable, but at the same time limited in the range of movement.

In this paper, we proposed a mother-son robot cooperation system to solve the problems mentioned above. A mother robot can carry son robots to a proper place near the target firstly during the operations under the water. When getting close to the target or encountering a narrow space that the mother robot cannot get through, it will reel out the son robots to get the target. A mother robot, which carried the power supply and the control circuit of the son robots, can provide the power supply to the son robots and control them by cables. Till now, there are fewer researches using this mother-son underwater robot cooperation system. Hence we designed and built a novel amphibious spherical robot as the mother robot to carry the microrobots actuated by ICPF actuators as son robots for collaboration. The spherical robot can move under the water as well as walk on land.

Compared to individual microrobots, mother-son robot system can perform a wide range of movement, by reason of spherical mother robot [11]-[15] having a relatively high moving speed and a long enduring time.

Compared to a single spherical robot, mother-son robot system can be applied in various practical environments, especially limited spaces. Compact structure of the microrobots can also provide a more precise control than spherical robots.

In comparison with other shapes, spherical robot has the maximum inner space. Besides, by having the symmetry, spherical robot has the advantage of flexibility [29] [30]. We proposed the design of the first generation of the spherical robot, which has the compact structure and the large inner space, in 2012. To improve the performance of the spherical robot, we redesigned the size of the structure. In this paper, we designed and developed a novel amphibious spherical mother robot in the first place. Then we did the force analysis of actuating units, which are water jet propellers, of the spherical robot and carried out underwater experiments to evaluate the spherical robot performance.

This paper consists of five parts. In section II, we described the mechanical design of the spherical robot and introduced the motion mechanisms of the robot under the water and on land. And force analysis of actuating units of the robot was done in this part. Then we performed the underwater evaluation for actuating system in section III. And a prototype was given in section IV and velocity experiments were conducted to evaluate the underwater performance. And

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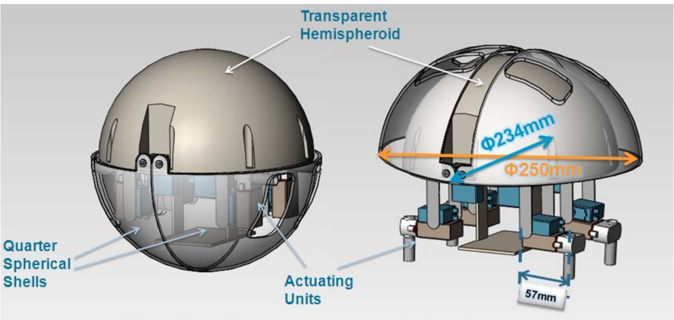
we discussed the results of the experiments. Finally, we drew the conclusions in section V.

II. MECHANICAL DESIGN

The mother-son robot system is a cooperation system, which composes of an amphibious spherical robot and several microrobots. During the underwater operation, mother robot moves to the target. When getting close to a narrow space, it keeps still for letting son robots out of it. After that, son robots will get into the narrow space like the pipeline and work in it by themselves. After the work finished, son robots will be taken back to the mother robot. In order to adapt to different environments, the mother robot is designed to be an amphibious spherical robot which can change the movement between water-jet mode and quadruped walking mode.

A. *Proposed Spherical Robot Structure*

The proposed spherical mother robot is composed of a sealed transparent hemispheroid, two openable transparent quarter spherical shells, a plastic circular plate, a plastic shelf and four actuating units. The control circuits and batteries and sensors are put in the sealed hemispheroid. Two quarter spherical shells are controlled by two servo motors to implement two spherical shells on and off simultaneously. The plastic plate is set for carrying the microrobots. Each actuating unit consists of a water jet propeller and two servo motors. Using these two servo motors that are mutually perpendicular in one actuating unit, each actuating unit can realize two degrees of freedom movement. As Fig. 1 shows, the diameter of the upper hemisphere is 234mm and the diameter of the lower hemisphere is 250mm.



(a) Horizontal motion pattern (b) Vertical motion pattern

Fig. 1 Spherical mother robot structure

B. *Actuating System Mechanisms*

The actuating system consists of four main actuating units. Each unit includes a water jet propeller, two servo motors and a stainless steel stand. As the mechanisms of the actuating system, the spherical mother robot can move both on land and under the water. The motor connected to the upper hemisphere is controlled to move in horizontal direction. While another motor fixed on the water jet propeller is controlled to move in vertical direction.

For the on-land walking movements, actuating units are considered as legs, each of which has two degrees of freedom. Three kinds of walking gaits have been adopted in the past research. The robot can realize the moving forward/backward and rotating motions on land like a quadruped robot in these three gaits. However, water jet propellers are used to be the actuators of the robot under the water. By controlling the rotating angles of the servo motors, spray angle of each water jet propeller can be changed to realize the moving forward/backward, rotating, floating and sinking motions. With this modularized design, a flexible amphibious actuating system in a compact size was realized.

Two servo motors, which are set on the surface of the plastic circular plate outside the upper hemisphere, are used to control the spherical shells on/off on land or under the water.

The force analysis was done to keep the durability of the chosen servo motors on the actuating units. Fig. 2 shows the force analysis on one actuating unit of the robot in horizontal motion, floating motion and sinking motion under the water. With changing the rotation angle of the vertical motor, thrust in all directions can be generated to realize the horizontal and vertical motions. By calculating the equation (1) and equation (2), actual torque of the motor can be gotten. Considering that the maximal torque forced on each servo motor cannot exceed its rated torque, we chose the appropriate servo motors.

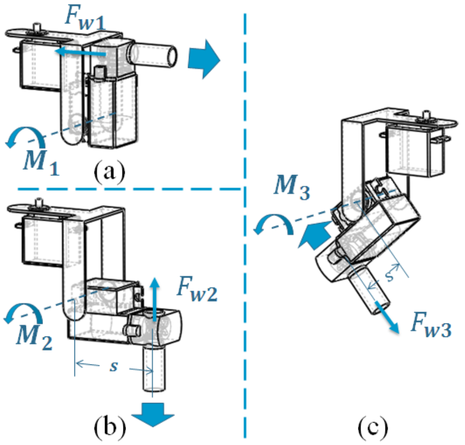


Fig. 2 Force analysis on one actuating unit in horizontal motion (a), floating motion (b) and sinking motion (c). Blue arrows indicate the water jet direction

$$\overrightarrow{M_1} = \overrightarrow{F_{w1}} \cdot s = \overrightarrow{F_{w2}} \cdot s = \overrightarrow{M_2} \tag{1}$$

$$\overrightarrow{M_3} = \overrightarrow{F_{w3}} \cdot s \tag{2}$$

Where: $\mathrm{F_{w1}}$, $\mathrm{F_{w2}}$ and $\mathrm{F_{w3}}$ are the thrust generated by water jet propeller, $\mathrm{M_1}$, $\mathrm{M_2}$ and $\mathrm{M_3}$ are the torque forced on the server motor, s is the moment arm of vertical motor.

For achieving the dynamic model of water jet propeller, we built a fluid model of water jet propeller [12], as shown in Fig. 3. The shaft of the motor, on which four blades are fixed, is perpendicular to the nozzle. Because of the small diameter of the nozzle, the velocity difference in the nozzle can be ignored. So, we consider the axis flow velocity V_a as a linear combine of incoming flow velocity V_i and the central flow velocity V_c. The axis flow velocity can be calculated by equation (3). In Fig, 3, Ω is the rotation velocity of motor shaft, V_i is the incoming velocity of flow, V_o is the outlet velocity of flow and D is the diameter of the nozzle.

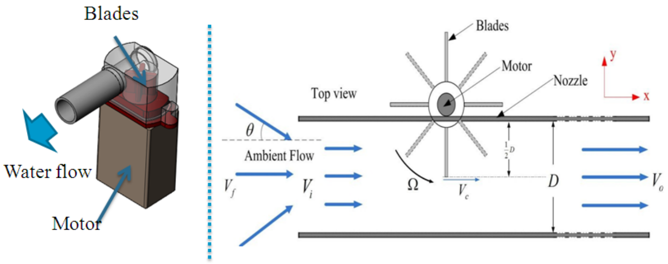


Fig. 3 Fluid model of water jet propeller

$$\begin{aligned} V_a &= k_1 V_i + k_2 V_c \\ V_i &= V_f \cos\theta \\ V_c &= \frac{1}{2} D\Omega \end{aligned} \tag{3}$$

Assuming that the flow is incompressible, according to the equation of continuity, we know that the volume of incoming flow must equal to the outlet flow, as equation (4) shows.

$$\rho_a V_a A_a = \rho_o V_o A_o \tag{4}$$

Where: the fluid density ρ_a and ρ_o are equal to ρ, the cross-section of the nozzle A_a is equal to A_o.

Hence, equation (5) can be derived.

$$V_a = V_o \tag{5}$$

By using the equation (6) and (7), we can calculate the thrust of the water jet propeller in two directions respectively. The thrust of flow passing through the long nozzle is larger than that passing through the opposite nozzle because of the difference of flow velocity.

$$F_{w1} = F_{w2} = \rho A {V_a}^2 \tag{6}$$

$$F_{w3} = \rho A {V_c}^2 \tag{7}$$

By substituting equation (3) in equation (6) and equation (7) respectively, equation (8) and equation (9) can be gotten to calculate the thrust.

$$F_{w1} = F_{w2} = \frac{1}{4}\rho\pi D^2({k_1}^2{V_i}^2 + k_1 k_2 \pi D V_i + \frac{1}{4}{k_2}^2 D^2 \Omega^2) \tag{8}$$

$$F_{w3} = \frac{1}{16}\rho\pi D^4 \Omega^2 \tag{9}$$

C. Control System Mechanisms and Batteries

The control center of the spherical robot is AVR ATMEGA2560 micro-controller. Ten channels of PWM signals are used to control the eight servo motors to drive the robot and two servo motors on the upper hemisphere to open and close two quarter spherical shells. Furthermore, eight Input/output ports are applied to control the four water jet propellers for motor forward and motor reversal. Using two data transmission ports, we can utilize the Analog to Digital Converter to receive and transmit the data with the micro-controller, which can control infrared proximity sensors and pressure sensors to realize the close-loop control. Another four Input/output ports are contacted to the remote controller with four channels which controls the movement of the robot.

For the power supply, we use three batteries, one of which, 6TNH22A/8.4V, is for providing the power to AVR micro-controller, other two of which, YBP216BE/7.4V, are used to provide the power to ten servo motors and four water jet propellers.

III. UNDERWATER EVALUATION FOR ACTUATING SYSTEM

For implementing the controllable thrust of the water jet propeller, by changing the duty of PWM signals the rotation velocity of the motor will change in a range. According to equation (8) and (9), we know that the thrust changes with the change of rotation velocity. For the purpose of the thrust control, experiments of horizontal thrust and vertical thrust were conducted to get the relationship between the duty of PWM signals and the thrust of motor.

A. Horizontal Thrust of the Robot

The mechanism of horizontal thrust experiments was designed based on leverage principle, as shown in Fig. 4. The electronic scale was used to measure the thrust of the robot. Assume that the length of two levers are a and b respectively, and the change number displayed on the electronic scale is m. Then we can get the thrust of the robot as:

$$F = \frac{mga}{b} \tag{10}$$

Where: a and b are the length of two levers respectively, m is the number displayed on the electronic scale.

During the moving forward/backward motions, two kinds of actuating mode are existed. The first actuating mode of the robot is to use the two actuating units opposite to the moving direction. The thrust of flow passing through the long nozzle is main thrust for the robot. However the second actuating mode of the robot is to use the other two actuating units. The thrust of flow passing through the opposite nozzle is assist thrust for the robot. Because the two units are inside the robot, part of the thrust will be offset by other components. So the assist thrust of the robot is relatively small. To gain a larger thrust, four units are actuated together for getting both main thrust and assist thrust.

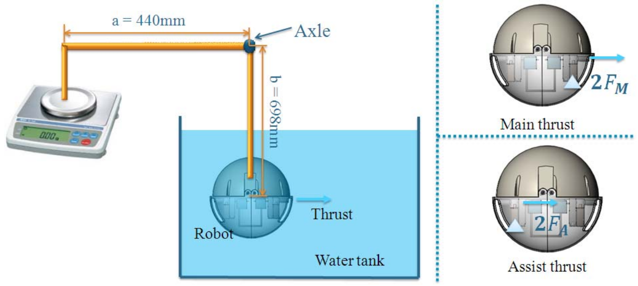
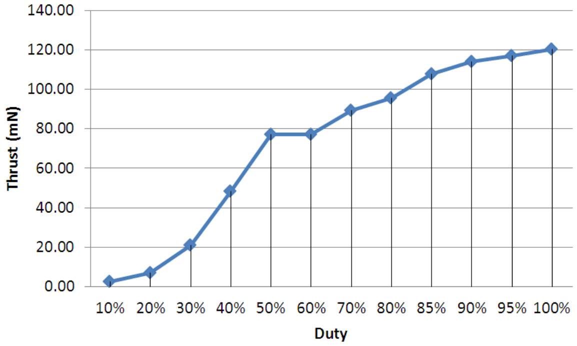
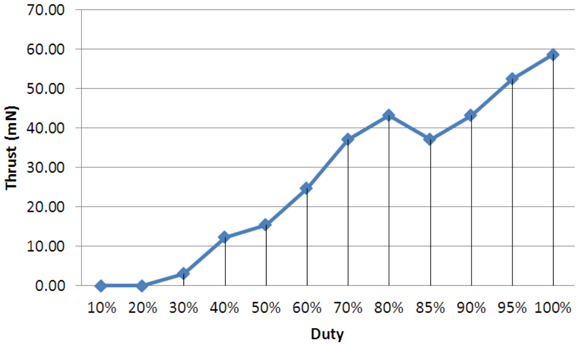


Fig. 4 Fluid model of water jet propeller. Blue arrows indicate the thrust direction. Blue triangles indicate the applied actuating units.

Fig. 5 shows the results of the horizontal thrust experiments. From the results of two graphs, the thrust is proportion to the duty of PWM signals. The maximal value of main thrust is 120mN. And the maximal value of assist thrust is 60mN, approximately half of the main thrust. The big difference between the two kinds of thrust is caused by the thrust loss. The maximal thrust of the robot is 180mN with actuating all the units.



(a) Main thrust



(b) Assist thrust

Fig. 5 Results of horizontal thrust experiments

B. *Vertical Thrust of the Robot*

Fig. 6 shows the designed mechanism of horizontal thrust experiments based on leverage principle. The electronic scale was also used to measure the thrust of the robot. Assume that the length of two levers are a and b respectively, and the change number displayed on the electronic scale is m. Then we can get the upward thrust and downward thrust of the robot by equation (10).

In the vertical thrust experiments, four actuating units are actuated to generate vertical actuating thrust. The vertical actuating thrust includes the upward thrust used to make the robot float and the downward thrust for sinking down. Compared with the moving forward motion, actuating four motors together can gain a relatively large actuating force. The maximal thrusts are 333.2mN and 362.6mN respectively.

Fig. 7 shows the results of the vertical thrust experiments. From the results of two graphs, the thrust is proportion to the duty of PWM signals. The trend of the curve is almost the same as that of the horizontal environments. The maximal value of upward thrust is 333.2mN. And the maximal value of downward thrust is 362.6mN, approximately same with the upward thrust. The theoretical value of the upward thrust should be 1.414 times larger than that of downward thrust. The direction of the buoyance of the robot leads to the difference between the two kinds of thrust. Both the horizontal experiments and vertical experiments proved that PWM control method is effective for underwater thrust control.

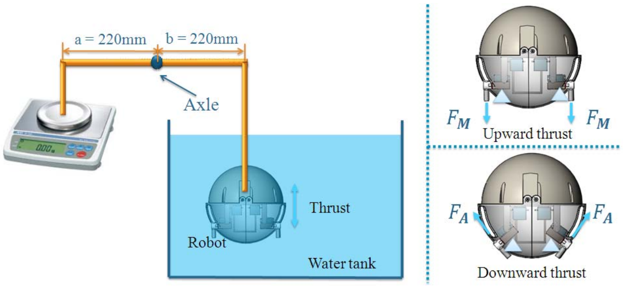
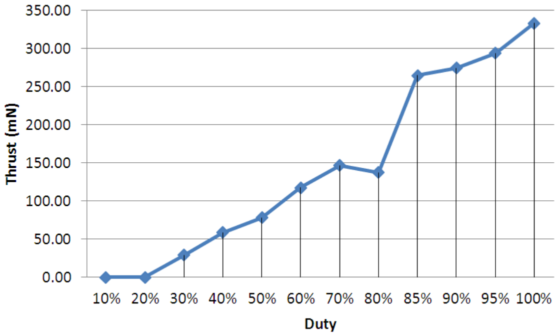
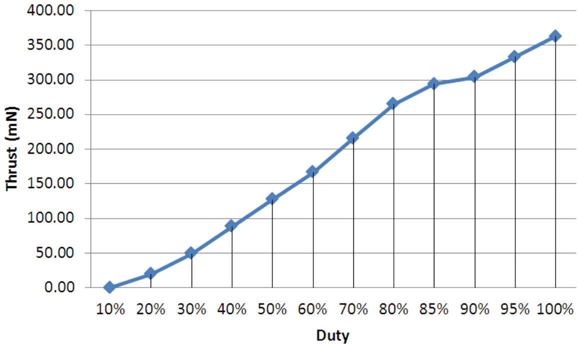


Fig. 6 Fluid model of water jet propeller. Blue arrows indicate the thrust direction. Blue triangles indicate the applied actuating units.



(a) Upward thrust



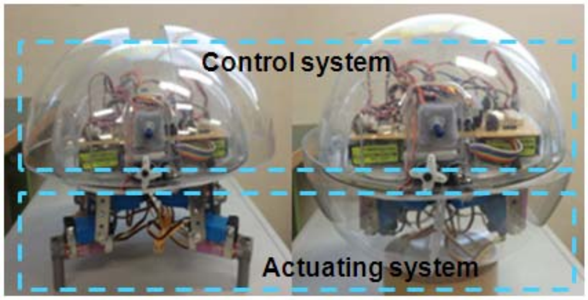
(b) Downward thrust

Fig. 7 Results of vertical thrust experiments

IV. PROTOTYPE SPHERICAL ROBOT AND VELOCITY EXPERIMENTS

A. *Prototype Spherical Robot*

Based on the structural design before, a prototype spherical mother robot was built, as Fig. 8 shows. The robot consists of two main parts, the upper hemisphere and two transparent quarter spherical shells. There is a buoyancy adjustment space in the top of the upper hemisphere. The control system is set in the sealed upper hemisphere to keep water proof. The actuating system and the holder for microrobots are set in the lower hemisphere. We chose to use HS-5086WP servo motors with the advantages of water proof. Due to the fact that the water jet propellers are non-waterproof, the propellers are made waterproof. The whole robot is 2.1 kg weight without additional bob-weight.



(a) Quadruped walking mode (b) Water-jet mode

Fig. 8 Prototype spherical mother robot

B. *Underwater Velocity Experiments*

During the underwater movements, two predictable conditions are existed, containing the semi-submerged state and submerged state. The semi-submerged state is a state that all necessary loadings are equipped and no additional bob-weight is added on the robot. The robot can float on water with approximately one-third of the body over the water surface. The submerged state is a state that additional bob-weight is added on the robot to keep it suspend in the water. In the past research, we built a theoretical model to calculate the underwater drag force exerted on the robot in these two states. And the relationship between the moving forward velocity and drag force was gotten.

The underwater velocity experiments of the robot in the semi-submerged state were conducted to evaluate the underwater performance of the robot. The experiments of moving forward for a distance of 1m were performed in a pool. By measuring the movement time, the average velocity of the robot can be calculated. In order to get an overall analysis for the robot, the moving forward experiments of the robot actuated by two main actuating units and four actuating units were done respectively.

Fig. 9 shows the experimental results. The blue line shows the moving forward velocities of robot under the control of two water jet propellers, which is in the same situation with the main thrust experiments discussed in section III. The red line shows the velocities of robot actuated by all the water jet propellers, which likes the situation that the thrust is the sum of the main thrust and assist thrust.

From the results, we know that PWM signals can control the underwater velocity smoothly. We got a maximal velocity of 16.1 cm/s under four propellers actuating, which is faster than the theoretical velocity. The reason is that the holes on the lower hemisphere for keeping the water jet propeller outside the body decreased the drag force. So, compared to the theoretical velocity, the actual velocity increased. The results also indicate that the difference between the velocity under four propellers actuating and that under two propellers is relatively small. Under a maximal duty of PWM signals, the difference is only 2.4cm/s. But the energy consumption is large under four propellers actuating. For realizing a high efficiency, we only use the main thrust in the moving forward motion. So, we got a maximal velocity of 13.7 cm/s under two propellers actuating.

Underwater experiments of rotating for an angle of 360º were also conducted in the pool. By measuring the movement time, we can calculate the average rotating velocity under different PWM control signals. Fig. 10 shows the results. As we know, the drag torque of a spherical robot is relatively small. So, the robot can realize a high rotating velocity. Under a duty of 100%, we got a maximal rotating velocity of 64.3º /s. The high rotating performance brings the robot flexible locomotion ability in the complicated environments.

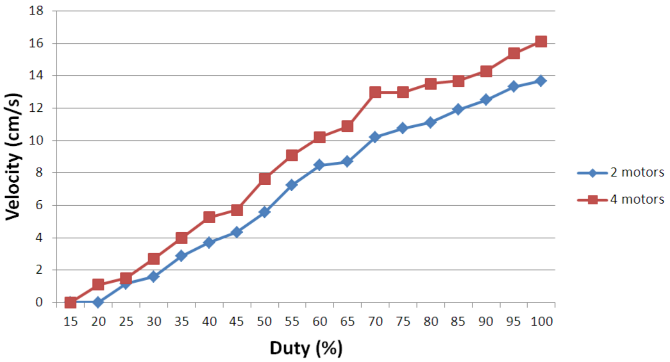


Fig. 9 Results of underwater moving forward experiments in the semi-submerged state

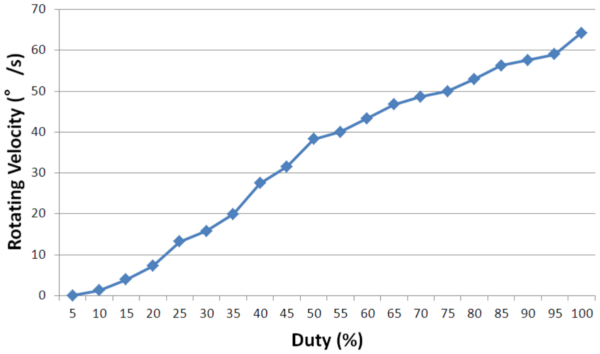


Fig. 10 Results of underwater rotating experiments in the semi-submerged state

V. CONCLUSIONS

In order to make up for the limitations of microrobots, a mother-son multi-robot system were proposed. And a novel amphibious spherical robot was designed. The robot can move under a relatively high velocity and in a relatively long time to transport microrobots, on land and under the water. And the spherical robot is used to control and provide the power to microrobots.

The spherical robot consists of an upper hemisphere, 234mm in diameter, for carrying the electronic devices, and two openable lower hemispheres, 250mm in diameter.

In this paper, plenty of underwater experiments of the robot in the semi-submerged state were conducted to evaluate the underwater performance, including the moving forward experiments in the moving forward experiments of the robot actuated by two main actuating units and four actuating units.

Before that, we did the underwater force analysis of the actuating system in horizontal direction and vertical direction. From the results, we know that the thrust is proportion to the duty of PWM signals. Under a duty of 100%, we got a maximal main thrust of 120mN and a maximal assist thrust of 60mN in horizontal direction. And the maximal thrust of the robot is 180mN with actuating all the units. From the results of vertical thrust experiments, the maximal upward thrust and downward thrust are 333.2mN and 362.6mN respectively.

From the results of the underwater moving forward experiments, we got a maximal velocity of 16.1 cm/s under four propellers actuating. For realizing a high efficiency, we only use the main thrust in the moving forward motion. So, we got a maximal velocity of 13.7 cm/s under two propellers actuating. From the results of the underwater rotating experiments, we got a maximal rotating velocity of 64.3° /s under a duty of 100%. And we know that PWM signals can control the underwater velocity smoothly.

ACKNOWLEDGMENT

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