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Development of a Spherical Amphibious Mother Robot

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***Abstract* – A variety kinds of underwater robots have been developed for the uses of underwater investigation and underwater operation. For those tasks in complicated or tiny underwater environments, some kinds of underwater microrobots have been developed. Thanks to the developments of smart actuators, microrobots realized relatively high performance within a compact structure. But problems in velocity and sustainable time limited their application. To solve this problem, we proposed a mother-son robot system, which include several microrobots as son robots, and an amphibious spherical robot as the mother robot. In this paper, a mother robot was proposed. It was designed to be able to walk on land, as well as move in water using a vectored water-jet mechanism. As the mother robot in the under-developing system, it also contained the space for transporting microrobots, and two openable hulls to protect the microrobots from the water currents and obstacles in water. A pressure sensor was used to determine whether robot was on land or in water, and measure the depth while in the underwater situation. To avoid obstacles, eight infrared distance sensors were used to detect obstacles in all the directions around the robot. In order to evaluate the robot`s underwater performance, some experiments were conducted.**

Index Terms* – *Spherical underwater robot. Amphibious robot. Mother-son robot system.

I. INTRODUCTION

Because of size, it is difficult for normal underwater robots to do micro operations, or simply move well in narrow environments. Microrobots actuated by smart actuators, such as ICPF actuators [1]-[4] and SMA actuators [5]-[8], have the advantage of a compact size, but their locomotion ability and sustainable time is poor. To solve these problems, we proposed a mother-son robot system. As shown in **Fig.1**, at the first of a task, the mother robot transporting microrobots inside of it move to a proper place near the destination where tasks will be conducted. The robot can move in water-jet mode or quadruped walking mode depending on the environment. Thus the robot can move both in water and on ground, and this expended the moving range of the whole system. After got near the destination, or encountered a narrow way which is hard to get through, the mother robot will take a stable gesture and act as a base station for microrobots. After that, microrobots, which were kept in the space inside the lower hemisphere of the mother robot before this step, will move out to conduct tasks by themselves. Because of the sizes of microrobots are small, they can be sent into very limited spaces, for example, narrow pipelines shown in Fig.1. Control units and batteries of microrobots are located in the mother robot, and cables are used between it and microrobots.

Compared to individual microrobots, there exist several advantages of this structure.

1) The moving range of the whole system is expended due to the relatively high moving speed and long enduring time of the mother robot.
2) Cables are used between mother robot and microrobots, so that microrobots can get a relatively stable power supply.
3) Because microrobots are all controlled by the mother robot, and can get communications with each other through mother robot, it is easier to conduct task in which multi-robot cooperation is needed.
4) Because power supply and control units are equipped in the mother robot, microrobots can realize a more compact structure with only actuating units and sensors.

And compared with the single large robot solutions, the final tasks are usually completed by microrobots in this mother-son robot system. So, it is easier for the microrobot to get across narrow environments and implement a relatively high control precision with legged locomotion.

Last year we reported the design of the first generation of mother robot. After that, in order to solve the problems in the mother robot, we redesigned the internal size while remained the outer size, added several sensors to realize close-loop control. In this paper, we will introduce the design of the new robot. And in order to evaluate the robot`s underwater performance, some experiments were conducted to measure the underwater propelling force.

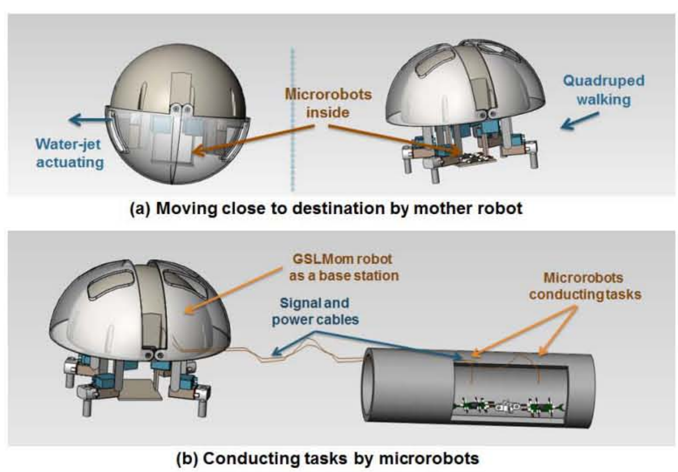


Fig. 1 Proposed mother-son robot system [19]

II. Design of the Mother Robot

A. General design

The basic design concepts of the mother robot including the following two points:

(1) Spherical. Spherical robot has the maximum inner space compared to other shapes. This is an important advantage when both compact structure and large inner space are needed. Besides that, spherical robot also has the merit of flexible in complicated environments because of symmetric.

(2) Amphibious. As a mother robot in the mother-son robot system, the robot should have a high locomotion performance in order to expend the moving range of the whole system. Thinking that the situations in shallow water or other similar environments are very common, we designed the robot an amphibious one.

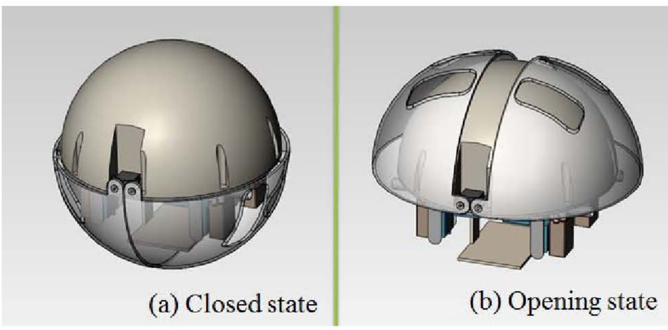


Fig. 2 The mother robot

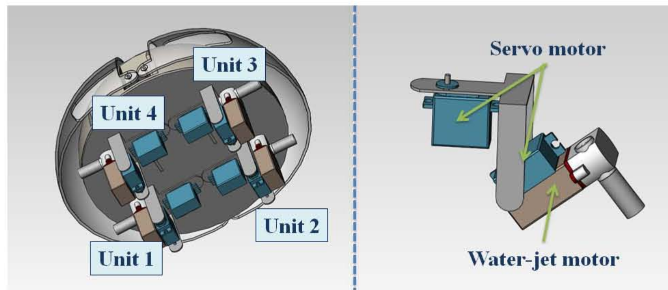
The robot including 3 functional parts: electrical control system, actuating system, and space for transport microrobots. For our amphibious robot, the actuating system and the space for microrobots are all equipped in the water exposure part. This is because: 1) the actuating system should realize locomotion both underwater and on the ground, thus a flexible structure is needed, and it is difficult for a structure equipped inside the water proof box to realize actuating flexibility. 2) microrobots need to be sent out from the mother robot to the underwater environment in some situations, and this procedure will be very unconvenient if the microrobots are placed inside the water proof box.

Due to the considerations on locomotion and space efficiency, we proposed a novel upper-lower structure. As shown in **Fig. 2**, the upper hemisphere is water proof and used as spaces for electronic circuits, while the lower hemisphere is spaces for actuating system and microrobots. And in order to realize locomotion on ground and the sending out of microrobots, the lower hemisphere is designed to be openable.

B. Actuating system

As shown in **Fig. 3**, the actuating system of mother robot is designed in a modularized structure. It contains 4 actuating units. Each unit contains one water-jet motor, two servo motors and a holder made of stainless steel. One single actuating unit can realize 2 DoFs motion on land, and can also generate a propelling force underwater using the water-jet mechanism.

In the walking motion, the actuating system can be used as four legs, each of them has 2 DoFs, while in the underwater situation, is can be seen as four vectored water-jet mechainsm, the two servo motors can control the orientation of the propelling force generated by water-jet motors. By using this modularized design, we successfully realized a flexible amohibious actuating system with in a compact size.



(a) Actuating system (b) Single unit

Fig. 3 Actuating system

Figure 4 shows the torques and forces on one single actuating unit while the robot is in the standing-up or walking state. In this state, the front point of the water-jet nozzle stand on the ground to support the robot and get the actuating force forward through friction. Here we difine F_1 as the actuating force forward and F_2 as the supporting force. These 2 forces are transmitted to the robot body through the torques generated by the 2 servo motors. T_1, T_2 were defined as the torques of horizontal servo motor and vertical servo motor, respectively. So we canobtain equation (1) and (2).

$$F_1 = T_1/L_1 \tag{1}$$

$$F_2 = T_2/L_2 \tag{2}$$

Where L_1 and L_2 are the distances from servo motor axises to the nozzle. **Figure 5** shows torques and forces during water-jet actuating mode. F_w is the actuating force generated by water-jet. The force is transmitted to the robot body through the torque generated by vertical servo motor. Also, we can obtain F_w from equation (3).

$$F_w = T_2/L_2 \tag{3}$$

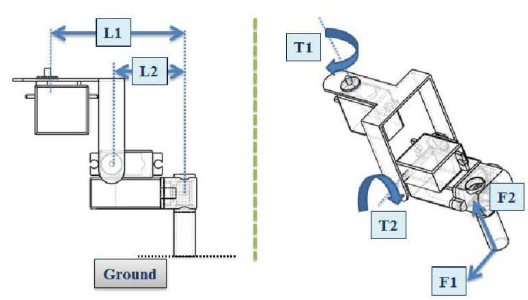


Fig. 4 Torques and forces on one actuating unit (standing)

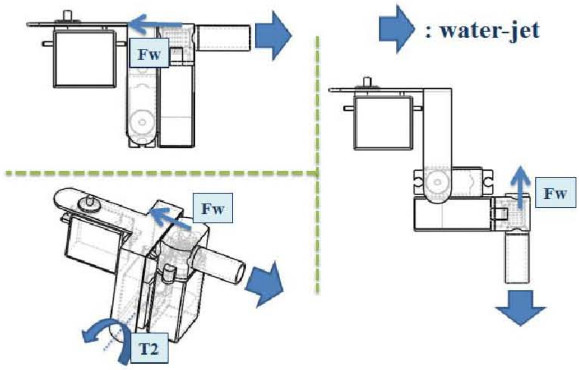


Fig. 5 Torques and forces on one actuating unit (water-jet)

C. *Control system*

Figure 6 shows the basic structure of the control system. An AVR micro controller is used as the CPU of the system. It generates 10 channels of PWM signals to control servo motors on the legs, and to control the opening/ closing of the lower hemisphere. Another 4 channels of PWM signal together with 4 channels of general I/O output were used to control the 4 water-jet motors. By using the PWM control method, we can control both the direction and the strength of water-jet. A 4 channel remote controller was used so that we can control the robot during experiments without rewrite the codes. Also, a 16 channel AD converter was used to support sensors to realize close-loop control.

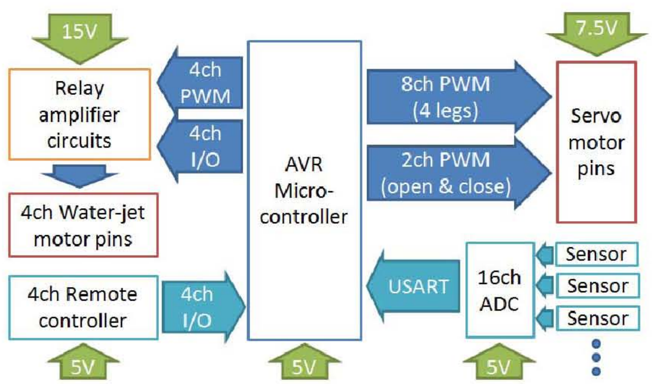


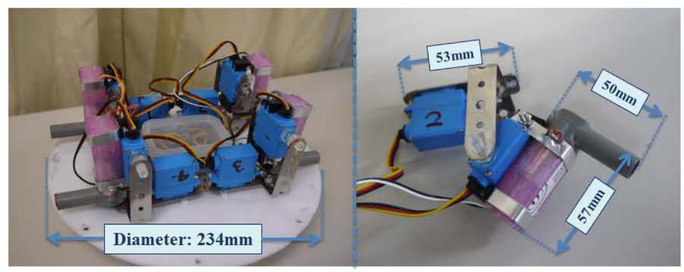
Fig. 6 Control system

A big problem for this structure is that different devices need different power supply. For CPU, remote controller and AD converter, a DC power supply of 5 V is needed. To realize stable control, we used an independent batteries and a regulator to power them. And then two 7.5 V batteries were used to power the motors. One was used to power the servo motors, while the serial connection of both the two batteries were used to generate a voltage of 15 V, to power the water-jet motors.

III. Prototype of Mother Robot

A. *Actuating system*

The prototype of actuating unit and actuating system is shown in **Fig. 7**. For the servo motors, we used HS-5086WP servo motor made by Hitec company. They are made to be water proof and can provide an output torque of 3.6kg*cm when the power supply is 6 V. The water-jet motor we used is a product of Raboesch company, and is sized 21*31*46mm^3 without nozzles. Water proof was conducted on servo motors and water-jet motors before assembling. The distances between servo motor axles to nozzle are L_1=95mm, L_2=45mm. Thus, the maximum supporting and driving force during walking and standing motion can be calculated out: driving force F_1= 3.7N, supporting force F_2=7.8N (single actuating unit). The maximum propelling force generated by one single water-jet motor is about 0.14N by experiment.



(a) Actuating system **(b) Single unit**

Fig. 7 Prototype actuating system

B. *Control system*

The basic structure of control system has been introduced in **Fig. 6**. **Figure 8** shows the prototype we developed in a compact structure. AVR ATmega2560 was used as the central controller.

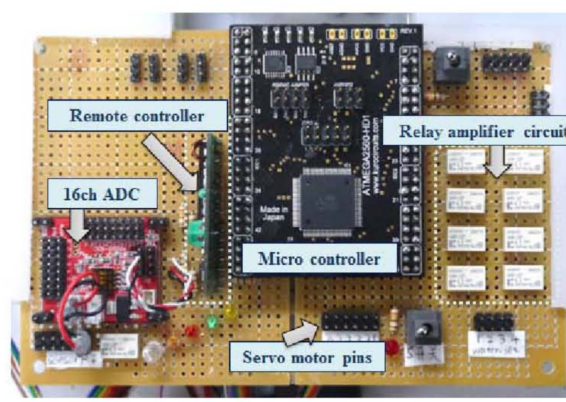


Fig. 8 Prototype control system

A Panasonic ADPW11 pressure sensor was added to the prototype mother robot. The sensor can be used to measure both air pressure and water pressure. As shown in Fig. 11, the sensor was fixed on the central board of the robot, with sensor body protected in the water proof upper hemisphere, and the sensing nozzle opened to the lower hemisphere. The analog output of the sensor can be converted to digital data by the 16ch AD converter, and then be sent to the micro controller.

By measuring the pressure outside the robot, we can get the following information:
(1) Whether the robot is on land or underwater.
(2) Depth of the robot in the underwater situation.
Thus we can realize a closed-loop control of the robot the change actuating mode or to adjust depth autonomously.

Distance sensor can monitor the distance from robot to obstacles to avoid collision. For our spherical amphibious robot, symmetry is a big advantage. For example, there is no difference between moving forward and backward for our robot. And for on land walking, the robot could even walk straitly leftward or rightward. So the sensor set up should also be symmetrical to take advantage of the symmetry of the robot. As shown in **Fig. 9**, 8 GP2Y0A21YK infrared distance sensors made by Sharp were used. They were fixed inside the upper hemisphere water proof space. According to the experiment, these sensors work well behind the transparent hull of the robot, and can transmit the distance of 0-80cm into analog signals.

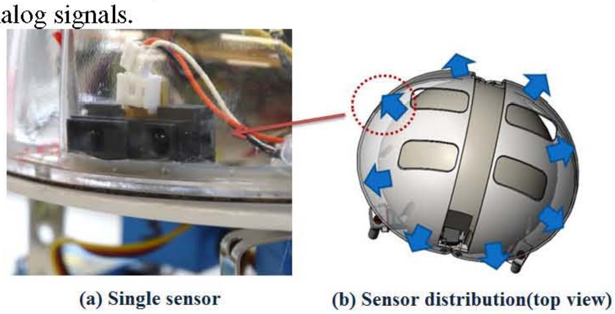


Fig. 9 Infrared distance sensor

C. Prototype mother robot

The prototype of mother robot is shown in **Fig. 10**. We can see that it is shaped by a water proof upper hemisphere, and two lower quarter-spheres. Their radius is different, with upper hemisphere R_u=117mm, and lower hemisphere R_l=125mm. Control system is located in the upper hemisphere, while the actuating system and the space for microrobots locates in the lower hemisphere. There is also a buoyancy adjustment space in the upper hemisphere. The whole robot weight 2.1kg.

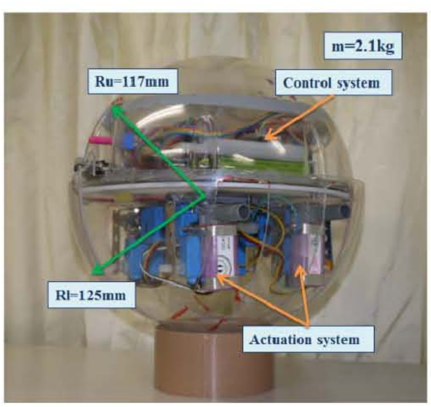


Fig. 10 The mother robot

IV. Underwater Actuating Assessment

A. Underwater propelling force

As introduced in chapter II, the propelling force of water-jet motor can be controlled by the duty of PWM signals. As the duty of the PWM signal increases, the angular velocity of water-jet blades increases. The increased angular velocity gives the water more power so that the propelling force increases. But this process also needs more torque outputted by the water jet motor, so the motor coil current also increases. So although there is no doubt that the increased PWM duty will result in higher propelling force, the relationship between them is very difficult to predict. So we designed experiments to make clear the relationship between PWM signal duty and propelling force.

Figure 11 shows the mechanism of the experiment a. We made use of leverage principle and used an electromagnetic scale to measure the actuating force of the water-jet motor. Assume the two arm of the lever is a and b respectively, and the reading of the electromagnetic scale is m, then we can obtain the actuating force F of the water-jet motor as equation (4).

$$F = {}^{\mathrm{mga}}/_{b} \qquad (4)$$

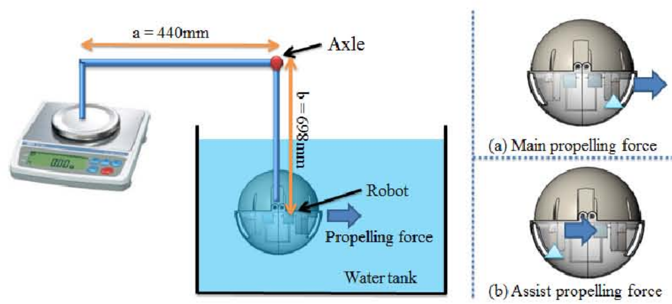
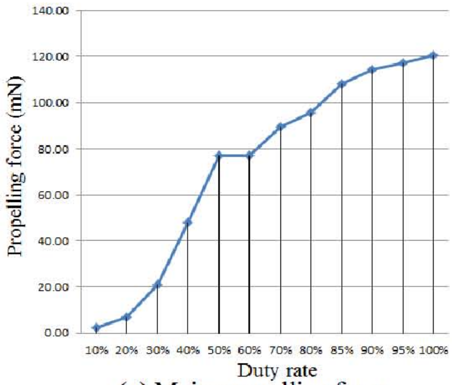


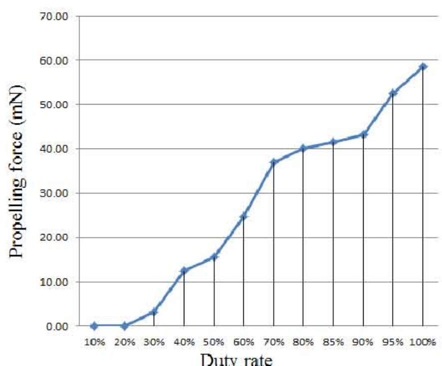
Fig. 11 Horizontal propelling force experiment

Two situations of horizontal actuating are considered. As shown in **Fig.11** (The blue triangle in the figure indicates the water-jet motors used in this situation):
Situation A: The main propelling force. The robot is actuated to move forward by the two water-jet motors in the back of the robot. The water can be jetted outside the robot body directly to generate a relatively large propelling force.
Situation B: The assist propelling force. The robot is actuated by the front two water-jet motors. In order to get an propelling force, water is jetted out of the water-jet motor but not outside the robot. The jetted water will meet the inside structures of the robot so that the propelling force is relatively small and not energy efficient. This propelling force can be used together with the main propelling force when a high velocity is needed, or be used as direction adjustment force in close-loop control.

Figure 12 shows the results. As we can see, as the duty of the PWM signal increases, the propelling force also increases. The maximum propelling force is 120mN in situation A, and 60mN in situation B. The assist propelling force is approximately half of the main propelling force. So 1.5 times of main propelling force can be get when the four water-jets motor are used together. The experiment also proved that the PWM control method is effective for underwater propelling force control.



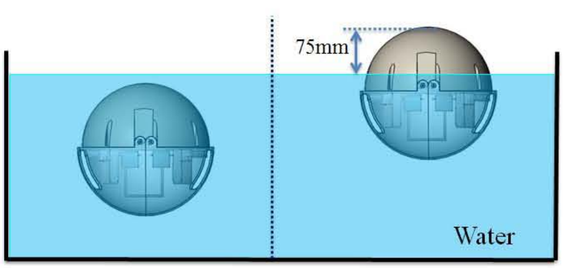
(a) Main propelling force



(b) Assist propelling force

Fig. 12 Horizontal propelling force results

The velocity performance of robot is also affected greatly by the drag force of the water. The maximum underwater velocity is the velocity when drag force equals propelling force. Drag force is affected by velocity and the status of robot in the water. Two possible situations can be predicted, they are shown in **Fig.13**. The half submerge state is the situation when all the necessary loadings are equipped and no extra weight is added on the robot. The robot can float on water with the top point 75mm higher than the water surface. The submerge state is the situation when some extra weight is added to the robot so that the robot can be suspended in water. The drag force in these two situations is different.



(a) Submerge (b) Half submerge

Fig. 13 Submerge and half submerge

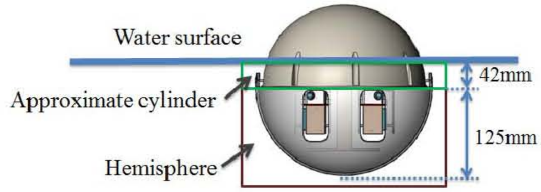


Fig.14 Drag force calculation of half submerge

Usually the underwater drag force can be calculated by equation (5).

$$D = \frac{1}{2} C_d(R_e)\rho v^2 A \qquad (5)$$

where C_d is the coefficient of drag, which is a function of Reynolds number and shape of the robot, ρ is the density of water, v is the velocity of the robot, and A is the section area of the underwater part in the direction of moving.

In the submerge situation, the robot can be seen as a ball with the diameter of 250mm, and in the half submerge situation, the robot can be analysis with the model shown in **Fig.14**. We consider the underwater part in half submerge situation as one hemisphere and one approximate cylinder. The drag force act on the hemisphere is half of that of the whole spherical robot. So the drag force here can be written as equation (6).

$$D_h = D_c + D_s/2 \qquad (6)$$

Where D_h, D_c, D_s are the drag forces act half submerged robot, the cylinder part and the whole submerged robot respectively.

In this study, the diameter of robot is 250 mm, and velocity in water is about 0.1-1 meter per second, so the Reynolds number is about $1*10^5$. Thus the coefficient of drag C_d of the ball is 0.4, and C_d of the cylinder part is 0.8 [14], according to the drag coefficient- Reynolds graph. So using the equation (5), we can obtain the following equations.

$$D_s = 9.8v^2 \qquad (7)$$

$$D_h = 8.6v^2 \qquad (8)$$

where v denotes the velocity of the robot.

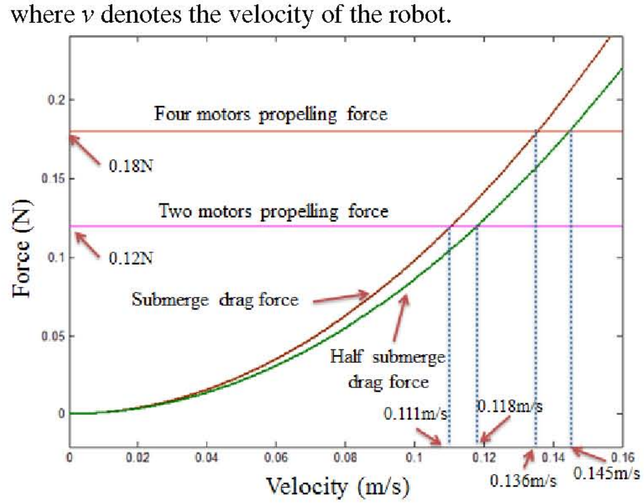


Fig. 15 Underwater propelling forces and drag forces

During underwater actuating, the drag force increases with the velocity, and the driving force is controlled by the motor usage and duty of PWM signal. In the forward actuating, the maximum driving force is 0.12N and 0.18N when using 2 water-jet motors and 4 motors, respectively. The maximum velocity can be got when the drag force equals driving force. This relationship is shown in **Fig.15**. According to this graph, when the driving force is 0.18N and the robot is in the half submerge state, a maximum velocity of 0.145m/s can be got.

V. Conclusion

In this paper, the conceptual structure of an improved spherical amphibious mother robot was proposed, and then the prototype robot was developed and evaluated experimentally. The robot is the second generation mother robot used in a mother-son robot system. It could move with a relatively high velocity and long sustainable time to transport microrobots, both on land and in underwater environments. Also, it could work as a base station to power and control microrobots during a task.

The mother robot consisted of one upper hemisphere with a diameter of 234mm, and two openable lower quarter hulls, which had a diameter of 250 mm. Both the control system of mother robot and microrobots were equipped in the water proof upper hemisphere.

A modularized actuating system which contained 4 actuating units was developed. Each unit contained one water-jet motor to generate underwater propulsive force, and 2 powerful servo motors which could support walking mechanism, as well as adjust water-jet orientation. With the help of this 4-unit actuating system, the mother robot possessed efficient amphibious locomotion ability. One pressure sensor and 8 infrared distance sensors were used to realize closed-loop control. To prove its feasibility, the obstacle avoidance experiment was carried out by using one distance sensor.

In order to evaluate the robot's underwater performance, some experiments were conducted to measure the underwater propulsive force. A theoretical model was also built to calculate the underwater drag force acted on the robot.

Acknowledgment

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