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Performance Evaluation on Land of an Amphibious Spherical Mother Robot

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Abstract - **Various underwater microrobots were used widely to work in limited spaces in the last few years. However, for having compact structures, the robots had some limitations of locomotion velocity and enduring time. In order to solve these problems, we proposed a mother-son robot cooperation system. We designed a conceptual structure of a novel amphibious spherical robot as the mother robot to carry the microrobots as son robots for collaboration. The spherical mother robot was composed of a sealed hemispheroid, two openable quarter spherical shells, a plastic circular plate, a plastic shelf and four actuating units. Each unit consisted of a water jet propeller and two servo motors, each of which could rotate 90° in horizontal or vertical direction respectively. The robot could perform walking and rotating motions on land, as well as moving forward and backward, rotating, surfacing and diving motions in water. We developed the prototype mother robot and did the force analysis of each unit of the actuating system. Then we proposed three walking gaits for the robot and carried out the walking experiments on the tile floor to evaluate the performance of the walking motion, including stability and velocity. From the experimental results of walking and rotating motions, we got that under a frequency of 3.33 Hz in Gait 3 (duty factor β=0.67), we got a maximal walking velocity of 22.5 cm/s. Under a frequency of 1.56 Hz in Gait 2 (duty factor β=0.75), we achieved a maximal rotating velocity of 71.29 °/s.**

Index Terms – Spherical robot, Amphibious robot, Water jet propeller, Quadruped walking, Mother robot, Walking gait.

I. Introduction

Nowadays, underwater robots are widely applied to survey the submarine topography, clean the pipeline, collect water samples, and recover underwater objects and so on. However, it is difficult for normal underwater robots to do operations in limited spaces. Utilize microrobots actuated by smart actuators including ICPF actuators [1]-[7] and SMA actuators [8]-[10] to work in narrow spaces for having the compact structure. But microrobots are limited in multi-functionality, locomotion velocity and enduring time. Microrobots usually have a lower speed because of the properties of the smart actuators. And it is hard for the wireless microrobots to get a long enduring time by having a compact structure that 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.

So we proposed a mother-son robot cooperation system to solve these problems. When doing the tasks under water, mother robot carries son robots to a proper place near the target at first. If 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 make them get the target. 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. In Japan, mother-son rescue robots using this system were built to replace people for collecting the information of the disaster survivors in dangerous places. 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 water as well as walk on land.

Compared to individual microrobots, this cooperation system has some advantages. As the spherical mother robot [11]-[15] having a relatively high moving speed and a long enduring time, the system can perform a very wide range of movement. In broad spaces, microrobots, which are carried on the spherical mother robot, are able to move in a high speed. While coming across a narrow space, spherical robot reels out the microrobots to get them to get through the limited space and conduct the tasks. Microrobots contact with the spherical robot by cables to obtain a relatively stable power supply. Microrobots with this cooperation system have more applications than without it. As loading power supply and control units on the spherical robot, microrobots can realize a more compact structure only with drive units and sensors.

Compared to a single spherical robot, mother-son 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. 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 proposed three walking gaits for the robot movement on land and carried out the walking experiments in four kinds of terrain to evaluate the performance of the walking motion with these three walking gaits, including stability and speed.

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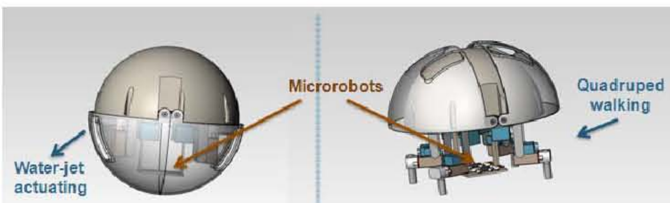
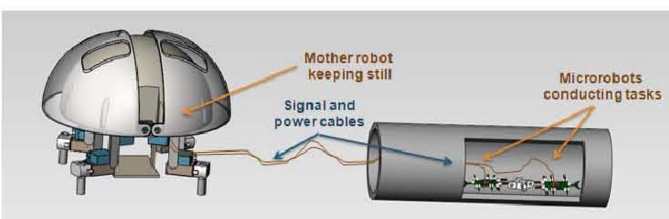
This paper consists of the following five parts. In section II, we described the structural design of the spherical robot and introduced the motion mechanisms of the robot under water and on land. And some force analysis of the robot was done in this part. Then we proposed three kinds of walking gaits and analyzed the characterization of each gait in section III. And a prototype was given in section IV and experiments were conducted to evaluate the performance of walking stability and velocity. And we discussed the results of the experiments. Finally, we drew the conclusions in section V.

II. Structural Design Of The Spherical Robot

The mother-son robot cooperation system composes of an amphibious spherical robot and several microrobots. The movement of the spherical robot can change between water-jet mode and quadruped walking mode for adapting to different environments. As shown in Fig.1, spherical robot moves close to the target and then keeps still for letting microrobots out of it. After that, microrobots will get in the narrow spaces like the pipeline and work in it by themselves. After finishing the work, microrobots will be taken back to the mother robot.



(a) Spherical mother robot moving close to the target



(b) Microrobots conducting tasks in limited spaces

Fig. 1 Mother-son robot cooperation system. (a) Spherical mother robot moving close to the target. (b) Microrobots conducting tasks in limited spaces

A. *Proposed Spherical Robot Structure*

The proposed spherical mother robot composes 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 realize two spherical shells on and off simultaneously. The plastic plate is set for carrying the microrobots. Each actuating unit is made of a water jet propeller and two servo motors. Using these two servo motors that are mutually perpendicular, each actuating unit can realize two degrees of freedom movement. As Fig.2 shows, the diameter of the upper hemisphere is 234 mm and the diameter of the lower hemisphere is 250 mm. The height of actuating unit in standing state is 108 mm, and the length of it is 85 mm.

B. *Actuating System Mechanisms*

As the mechanisms of the actuating system, the spherical mother robot can move both on land and under water. The actuating system consists of four main actuating units. Each unit includes a water jet propeller, two servo motors and a stainless steel stand. 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.

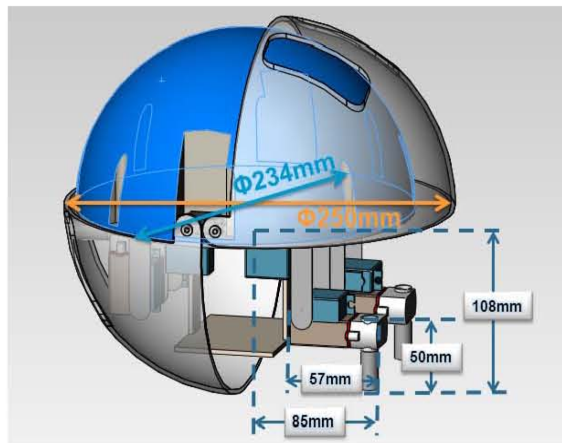


Fig. 2 Spherical mother robot structure

For the walking movements on land, actuating units are considered as legs, each of which has two degrees of freedom. The robot can realize the moving forward/backward and rotating motions on land like a quadruped robot. However, under water, water jet propellers are the actuators of the robot. By controlling the rotating angles of the servo motors, spray angle of each water jet propeller can be changed to realize the moving forward and backward, rotating, rising and diving motions.

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 open or closed on land and under water.

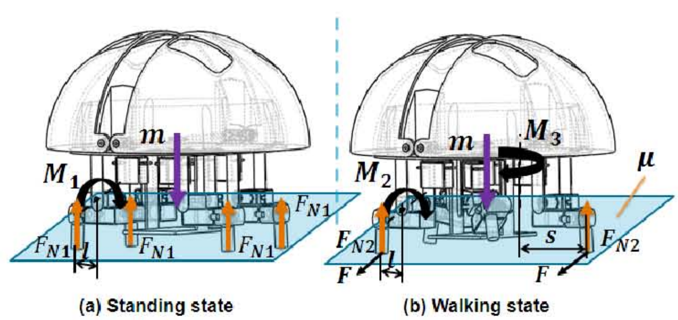


Fig. 3 Force analysis on land (a) standing state and (b) walking state

For choosing the appropriate servo motors used on the four legs of the robot, we did the following force analysis and calculations. Fig. 3 shows the force analysis of the robot on land. When the robot in standing state, each vertical servo motor will be forced on the torque of M_1. And in walking state, each vertical servo motor of the still legs and each horizontal servo motor of the moving legs will be forced on the torque of M_2 and M_3 separately. Here we pretended that in one moment the supporting force forcing on each leg contacting with the ground is the same. Considering that the torque forced on each servo motor cannot exceed its rated torque, M, we did the calculations as follows.

$$mg = 4F_{N1} = 2F_{N2} \tag{1}$$

$$M_1 = F_{N1} \times l \tag{2}$$

$$M_2 = F_{N2} \times l \tag{3}$$

$$M_3 = F \times s = \mu F_{N2} \times s \tag{4}$$

Where: F_{N1}, F_{N2} are the normal force exerted by each surface, F is the force of friction, μ is the friction coefficient of the contact surface, l is the moment arm of vertical motor, s is the moment arm of horizontal motor.

$$\max(M_1, M_2, M_3) < M \tag{5}$$

The upward force of F_N is different depending on the different walking gaits. As equation (1) shows, the force of F_{N1} is the minimal force which supports the ground, when robot stand with four legs. While the robot walks on land, there is an instant that only two legs of the robot contact with the ground. The supporting force is F_{N2}, which is maximal supporting force. After made sure that equation (5) holds, we choose this kind of servo motor.

C. Sensing Mechanism

As an intelligent robot, the mother robot can detect and avoid all the obstacles around it by using the proximity sensors. For having the symmetrical characteristic, spherical robot can move in any directions by spinning on the spot. So sensors should be set up on bottom of the upper hemisphere next to the transparent hull symmetrically. In this paper, 8 GP2Y0A21YK infrared proximity sensors made by Sharp are used to detect all the obstacles around the robot.

Because of the amphibious characteristic, the mother robot should have an ability of doing environment judgment, on land or under water. A Panasonic ADPW11 pressure sensor which can measure the air pressure and water pressure is added to the robot. We fix the pressure sensor on the plastic circular plate for measuring the pressure to judge the environment around the robot and do depths test.

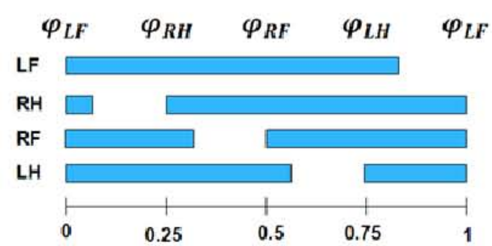
D. Control System Mechanisms and Batteries

The control center of the spherical robot is AVR ATMEGA2560 micro-controller. We use ten channels of PWM signals to control the eight servo motors on the legs to actuate the robot, and two servo motors on the upper hemisphere to open and close two quarter spherical shells. And eight Input/output ports are used to control the four water jet propellers for positive rotating and negative rotating. 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.

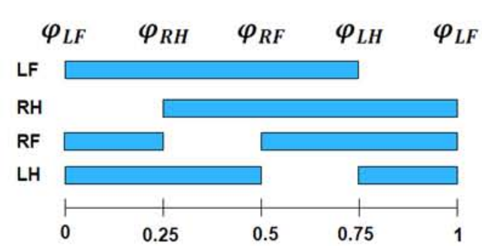
For the power supply, we use three batteries, one of which, 6TNH22A/8.4 V, is for providing the power to AVR micro-controller, other two of which, YBP216BE/7.4 V, are used to provide the power to ten servo motors and four water jet propellers.

III. Gait Characterization

For the quadruped robots, several walking gaits [16] are existed. The first walking gait is a statically stable regular symmetric gait, that a leg in the air is set down (event φ) before the next one is lifted, with at least three legs contacting with the ground at all times. Accordingly, the gait event sequences and the gait timing sequences can be defined by the duty factor β, and the relative phase of the left hind leg, φ_{LH}. The relative phases of all the legs are set that φ_{LF} is 0, φ_{RF} is 0.5 and RH has a phase difference of 0.5 with LH. Fig. 4(a) shows the event sequences of the first walking gait following the duty factor β of 0.8. And the relative phases for the legs of the first walking gait are depicted in Fig. 5(a).



(a) Gait 1 with the duty factor β = 0.8



(b) Gait 2 with the duty factor β = 0.75

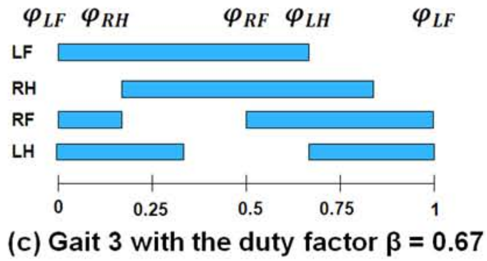


Fig. 4 Event sequences of one step cycle for different gaits. The legs: LF, left foreleg; RF, right foreleg; LH, left hind leg; RH, right hind leg. Blue bars indicate that legs contact with ground

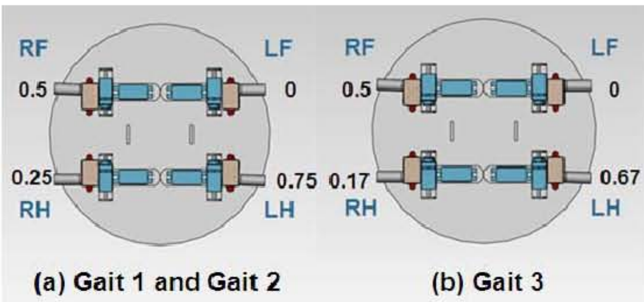


Fig. 5 Relative phases of one step cycle for different gaits (bottom view)

The second and third walking gaits follow a rule that the front leg is lifted while the ipsilateral hind leg is set down, which can achieve a maximal stability margin. The rule means that the relative phase of the left hind leg φ_{LH} follows the duty factor β.

The duty factor of the second walking gait is set to 0.75, which can achieve a maximal time of contacting the ground among the walking gaits following the rule. As Fig. 4(b) shows, the second walking gait is a special one. In this gait, there are three legs contacting with the ground all the time and when one leg is lifted up, the following leg is put down at the same time. And the relative phases for the legs of the second walking gait are the same as that of the first gait, which are depicted in Fig. 5(a).

As the speed increases, the duty factor decreases. As shown in Fig. 4(c), the duty factor of the third walking gait is set to 0.67. And the relative phases for the legs of the third gait are depicted in Fig. 5(b). There is a moment that the robot only uses two legs to support the body.

$$v = d * f \tag{6}$$

$$d = (\frac{\theta}{180} * \pi * s)/\beta = 0.1483 * \theta/\beta \tag{7}$$

Where: v is the velocity of the robot, d is the step size of the robot, f is the frequency of one step cycle, β is the duty factor of the gait timing sequences, θ is rotating angle of the horizontal motor.

As equation (6) shows, the velocity of the robot is related to the step size of the robot and frequency of one step cycle. And the step size is in proportion to the rotating angle of the leg that is the rotating angle of the horizontal motor and duty factor of the gait timing sequences, as shown in equation (7). Hence, the velocity of the robot is decided by the frequency and duty factor.

For evaluating the performance of the three kinds of gaits, we did the stability experiments under different control frequencies. In order to evaluate the performance of the robot, velocity experiments in three walking gaits were conducted. In the next part, we will introduce the analysis of the experimental data.

IV. Prototype Spherical Robot And Experiments

A. *Prototype Spherical Robot*

A prototype spherical mother robot was constructed, based on the structural design before, as shown in Fig. 6. 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 actuating system and the holder for microrobots were set in the lower hemisphere. We chose to use HS-5086WP servo motors made by Hitec Company, which have the advantages of water proof. The water jet propellers we used are non-waterproof, which are the products of Raboesch Company. The whole robot is 2.1 kg weight.

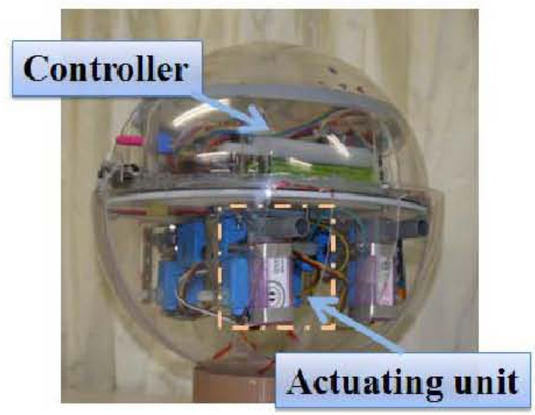


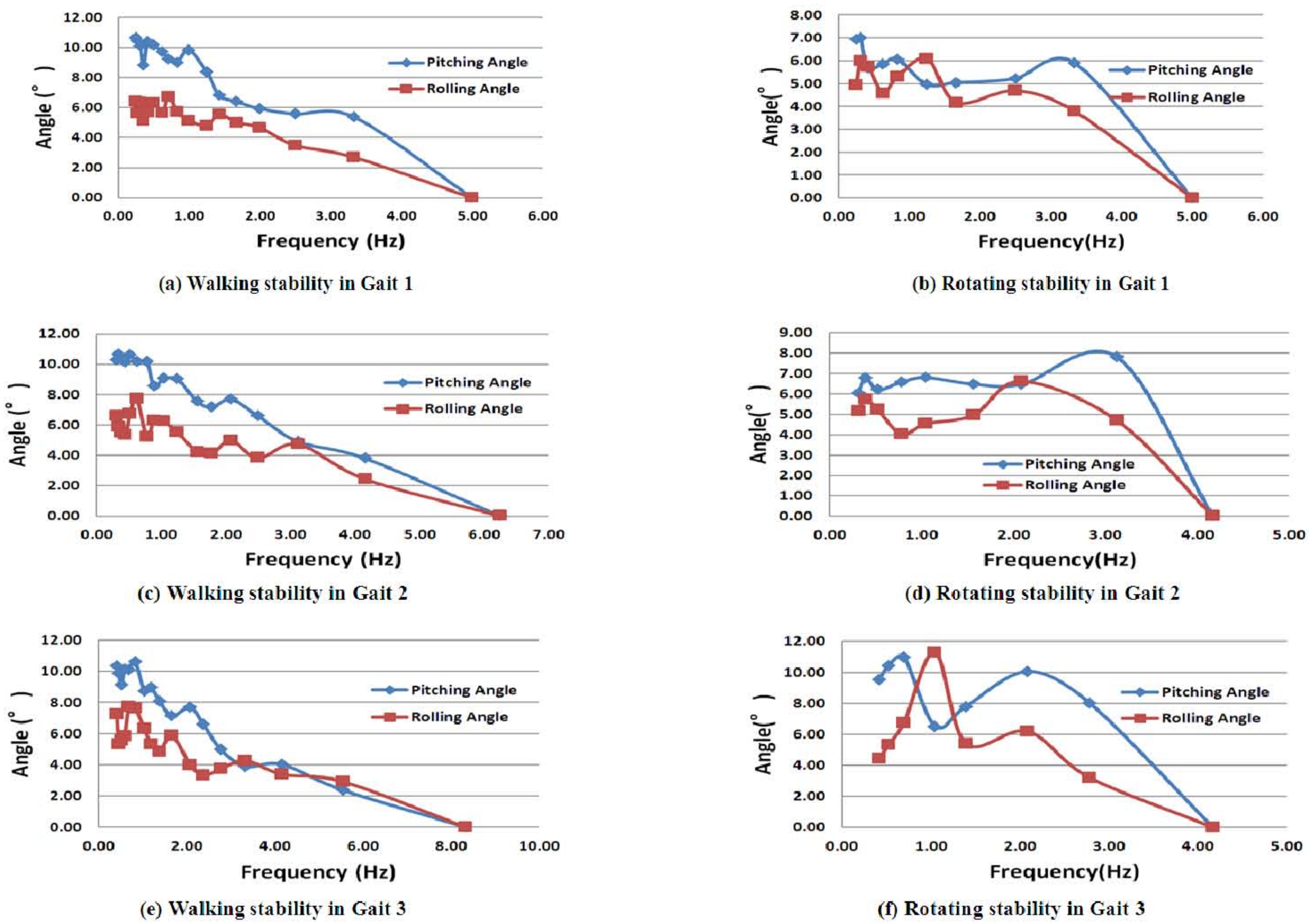
Fig. 6 Prototype spherical mother robot

B. *Walking Stability and Velocity Experiments*

Stability and velocity are two principal elements to evaluate the movement of the spherical robot. In order to evaluate the performance of the robot, we did the walking stability and velocity experiments to these two principle elements. For testing the stability of the robot, we use an MTx sensor to monitor the vibration in walking motion and rotating motion. We controlled the robot to walk for 1 m and rotate for 180 degrees on the tile floor.

Fig. 7 shows the peak to peak amplitude of robot body vibration during walking and rotating motions. The blue points indicate the vibration data in pitching direction, and the red points indicate the vibration data in rolling direction. These data was got by the MTx sensor. From the results of the graphs, vibration of walking motion in two directions is in proportion to the frequency separately in there different gaits. Under a relatively high frequency, the body can attain a stable condition in walking motion. In Gait 1 and Gait 2, with the frequency increasing, the vibration amplitude can change little in rotating motion. While in Gait 3, with frequency changing, the variation of vibration is severe, which means the rotating motion is unstable. Gait 1 provides the most stable movement than other two gaits generally. However under a high frequency, Gait 3 embodies an advantage of stability of walking motion in pitching direction.

There are three reasons that influence the stability of the robot. Because of having an instant that the robot only uses two legs to support the body in Gait 3, as we know, two legs cannot provide a stable state for the robot, so it will cause the robot unstable. So with the frequency increasing, the vibration decreases. Another reason is that for keeping the momentum conservation of the robot body during walking, the body will generate vibration. And the instantaneous driving force applied on the robot will generate the vibration too. The vibration amplitude will change little with the increasing frequency.



(a) Walking stability in Gait 1

(b) Rotating stability in Gait 1

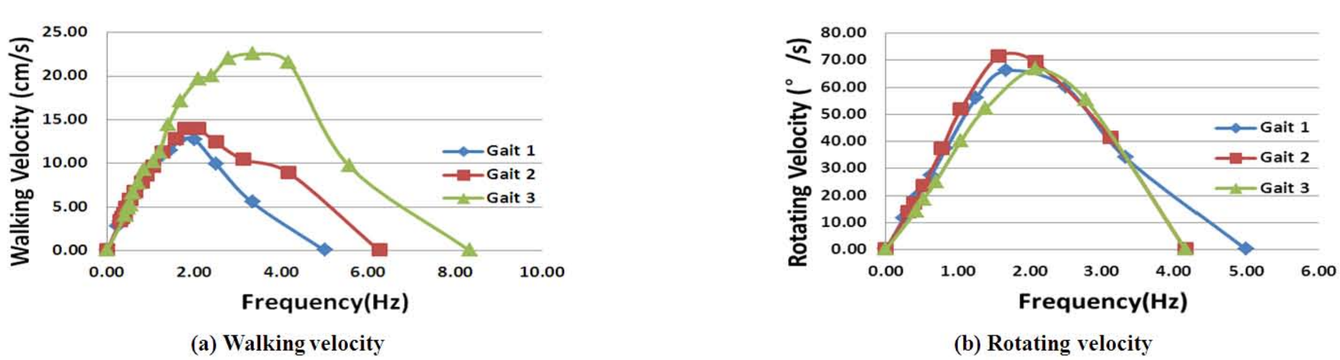
(c) Walking stability in Gait 2

(d) Rotating stability in Gait 2

(e) Walking stability in Gait 3

(f) Rotating stability in Gait 3

Fig. 7 Vibration amplitude in walking and rotating motions



(a) Walking velocity

(b) Rotating velocity

Fig. 8 Experimental results in walking and rotating motions

The walking velocity and rotating velocity of the robot under different frequency with different gaits are shown in Fig. 8. The blue, red and green points show the speed of Gait 1, Gait 2 and Gait 3 respectively. As the graphs show, with the frequency increasing, the walking velocity will increase at first and then decrease to zero in each walking gait. So does the rotating velocity. And under a relatively low frequency, the walking velocities in three gaits are roughly equal. While under a relatively high frequency, walking velocity increases by changing the gait from Gait 1 to Gait 3. The rotating velocity is only affected by the control frequency. That is because that by changing the walking gait from Gait 1 to Gait 3, the motion will become more and more unstable. Although the frequency increases, by the reason of the step size decreasing and vibration, the rotating velocity decreases.

V. CONCLUSION

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

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

Under a relatively high frequency, the body can attain the most stable condition in walking forward motion. Gait 1 provides the most stable movement than other two gaits generally. However under a high frequency, Gait 3 embodies an advantage of stability of walking motion in pitching direction.

Under a relatively low frequency, the walking velocities in three gaits are roughly equal. While under a relatively high frequency, walking velocity increases from Gait 1 to Gait 3. The rotating velocity is only affected by the control frequency. Under a control frequency of 3.33 Hz in Gait 3, we got a maximal walking velocity of 22.5 cm/s. Under a frequency of 1.56 Hz in Gait 2, we achieved a maximal rotating velocity of 71.29 °/s.

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