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Development of an Amphibious Turtle-Inspired Spherical Mother Robot

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Abstract

Robots play an important role in underwater monitoring and recovery operations, such as pollution detection, submarine sampling and data collection, video mapping, and object recovery in dangerous places. However, regular-sized robots may not be suitable for applications in some restricted underwater environments. Accordingly, in previous research we designed several novel types of bio-inspired microrobots using Ionic Polymer Metal Composite (IPMC) and Shape Memory Alloy (SMA) actuators. These microrobots possess some attributes of compact structure, multi-functionality, flexibility, and precise positioning. However, they lack the attributes of long endurance, stable high speed, and large load capacity necessary for real-world applications. To overcome these disadvantages, we proposed a mother-son robot system, composed of several microrobots as sons and a newly designed amphibious spherical robot as the mother. Inspired by amphibious turtles, the mother robot was designed with a spherical body and four legs with two Degrees of Freedom (DOF). It is actuated by four vectored water-jet propellers and ten servomotors, and it is capable of walking on land and cruising underwater. We analysed the mother robot's walking and underwater cruising mechanisms, constructed a prototype, and carried out a series of experiments to evaluate its amphibious motions. Good motion performance was observed in the experiments.

Keywords: amphibious robot, biomimetic underwater robot, mother-son robot system, spherical robot, vectored water-jet propeller

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1 Introduction

Robots are now widely used to implement underwater tasks considered by humans to be dangerous, dull, or dirty, primarily because of their long endurance, stable high speeds, and large load capabilities. This trend has continued into underwater monitoring and recovery operations, including pollution detection, submarine sampling and data collection, video mapping, exploration of unstructured underwater environments, object recovery in dangerous places, and other tasks[1–3]. However, when a robot is used in a complicated underwater environment, such as a narrow pipeline or a region filled with reefs, it requires the combined attributes of endurance, stable high speed, large load capability, flexibility, compact structure, and multi-functionality. Regular-sized robots are not suitable for applications in limited spaces, so microrobots have been developed using special actuator materials instead of motors. Their compact size allows them to operate in very limited underwater spaces.

In recent years, microrobot researches have been carried out in all parts of the world, and are becoming increasingly popular in the field of robotics. A number of trade-offs must be made when constructing robots with compact sizes, and important capabilities (such as locomotion and endurance) must be sacrificed. To solve these problems, a variety of smart materials, such as Ionic Polymer Metal Composite (IPMC), piezoelectric elements, pneumatic actuators, and Shape Memory Alloy (SMA), have been investigated for use as artificial muscles in new types of microrobots[4–10]. Robots have

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been developed with compact size, new motion methods, and low working energy consumption[11–19].

Although numerous achievements have been made in microrobot kinematics and control, microrobots remain inadequate for many practical tasks. The first reason is that the velocities of these robots are still very low, which limits their working area. It would be difficult for microrobots travelling at a velocity of a few millimetres per second to reach a distant target position. The second reason is the power supply problem. Because of the trade-off between microrobot size and battery volume, the endurance of the power supply is limited. Although solutions such as Electro Mechanical Actuators (EMA) actuation[20] and wireless power[21] have been reported, large outside devices are required in these situations. The last reason is that it is difficult to implement intelligent control or multi-micro robot cooperation without an adequate array of sensors, which is impractical under low load capability.

To combine the attributes of microrobots, such as compact structure, multi-functionality, flexibility, and precise positioning, with the attributes of regular-sized robots, such as stable high speed, long endurance, and large load capacity, we propose a mother-son robot system, which includes several microrobots as sons and a newly designed amphibious spherical robot as the mother[22,23]. This is an original idea, inspired by the design of aircraft carrier systems. The mother robot can be used as a carrier to transport the microrobots to the target position, and provides a power supply and/or control for the microrobots. When the mother robot reaches the desired location, or encounters a narrow channel that is difficult to traverse, it takes up a stable position and acts as a base station for the microrobots. The microrobots then exit the mother robot, proceed to the target position, and carry out their tasks.

To implement the mother-son robot system, we also designed several novel types of underwater microrobots, inspired by various insects and marine animals using IPMC and SMA actuators. These microrobots possess some of the attributes of compact structure, multi-functionality, flexibility, and precise positioning[24–30]. In the present paper, we focus on the regular-sized mother robot.

Many types of regular-sized underwater robots with streamlined designs are suitable for high-speed cruising. While the movement of some of these robots involves changing the angles of rudders or adjusting the differential propulsive forces of thrusters, a number of vectored propeller-actuated underwater robots were introduced[31]. A multi-channel Hall-effect thruster was also reported, involving vector composition of underwater robots[32]. Additionally, we developed a spherical underwater robot equipped with three vectored water-jet-based thrusters[3].

Various configurations, shapes, and sizes of underwater robots are required for different applications. For use in very complicated underwater environments, such as narrow pipelines or regions filled with reefs, the mother robot needs to have the attributes of flexibility, compact structure, and multi-functionality in addition to long endurance, stable high speed, and large load capability.

Inspired by amphibious turtles, the mother robot was designed to have a spherical body and four legs. It is actuated by four water-jet propellers and ten servomotors, and it is capable of a walking on land and tri-directional cruising underwater. The spherical body can rotate and change direction more easily than a streamlined design, which is very important for the mother robot in restricted spaces. Additionally, the spherical structure allows a relatively large interior space for the microrobots. To expand the range of motion of the overall system, the four legs not only implement walking and rotating motions on land, but also actuate the robot to cruise forward and backward, rotate around its geometrical centre, and surface/dive in underwater environments.

The remainder of this paper is organized as follows. First, we propose the mother-son robot system and describe the feasibility results from several previously developed microrobots. Second, we introduce a new type of spherical mother robot, which was inspired by amphibious turtles and has one hemisphere, two quarter-spheres, and four legs with two DOF, which can walk on land and tri-directionally cruise underwater. We also explain the opening and actuating mechanisms of the mother robot. Third, we provide a detailed analysis of the walking motion on land and the tri-directional cruising motions in the underwater environment. Fourth, we discuss the development of a prototype of this underwater robot, together with a series of experiments to evaluate the walking motion on land, surging motion in the horizontal plane, and turning motion. Finally, we present our conclusions.

2 Amphibious spherical mother robot

2.1 Basic requirements and bio-inspired structure

In the mother-son robot system, the mother robot needs to have the following characteristics: (1) high locomotion ability to extend the range of movement of the whole system; (2) interior space and load capacity are large enough to simultaneously accommodate the control circuit, actuating system, power supply, microrobots, and control system for the microrobots; and (3) a compact structure to approach a target position located in a narrow or complicated environment.

Nature provides perfect models for robots. The senses and structures of many biomimetic robots are based on animals such as insects, fish, or birds[33–36]. Turtles are reptiles of the order Testudines, characterised by a special bony or cartilaginous shell that develops from their ribs and acts as a shield. The upper shell of the turtle is called the carapace, while the lower shell, which encases the belly, is called the plastron. The carapace and plastron are joined at the turtle's sides by bony structures called bridges. Amphibious turtles normally have four feet, which are webbed and often have long claws. They can walk on land or along the bottom of a river or lake. While swimming underwater, these turtles use all four feet in a manner similar to a dog paddle. The feet on the left and right sides of the body alternately provide thrust[37].

Inspired by amphibious turtles, the mother robot was designed with a spherical body and four legs to satisfy above requirements[37]. The spherical structure can rotate with a 0 rotational radius; it can also change its direction more easily than traditional streamlined structures, and has a relatively large interior space compared to other shapes. That is an important attribute when both compact structure and large carrying capacity are required. The four legs are actuated by servomotors and water-jet propellers to implement a walking motion on land and tri-directional cruising motions in water. Thus, the mother robot possesses a large load capacity and extends the range of motion of the son microrobots.

2.2 Spherical structure design

The proposed amphibious spherical robot is composed of one hemisphere, two quarter-spherical hulls, and four legs. Each leg is actuated by two servomotors and one water-jet propeller. The two servomotors are installed perpendicular to each other, one in the horizontal plane, and the other in the vertical plane. Each water-jet propeller can be actuated by the two servomotors, so the direction of the jetted water can be changed both in horizontal plane and vertical plane, either sequentially or simultaneously. The two quarter-spherical hulls are actuated by two more servomotors, which implement the opening and closing motions. When the robot is in the walking mode, or needs to release the microrobots at the target position, the two hulls open. The actuating system and the supporting platform for the microrobots are then directly exposed to the outside.

All control units and batteries are installed in the upper hemisphere, which is waterproofed. The actuating system and the supporting platform are installed in the interior of the lower hemisphere, which communicates with the outside through gaps and holes in the two quarter-spherical hulls. Each quarter-spherical hull has two long holes, allowing the water-jet system to work normally when the hulls are closed.

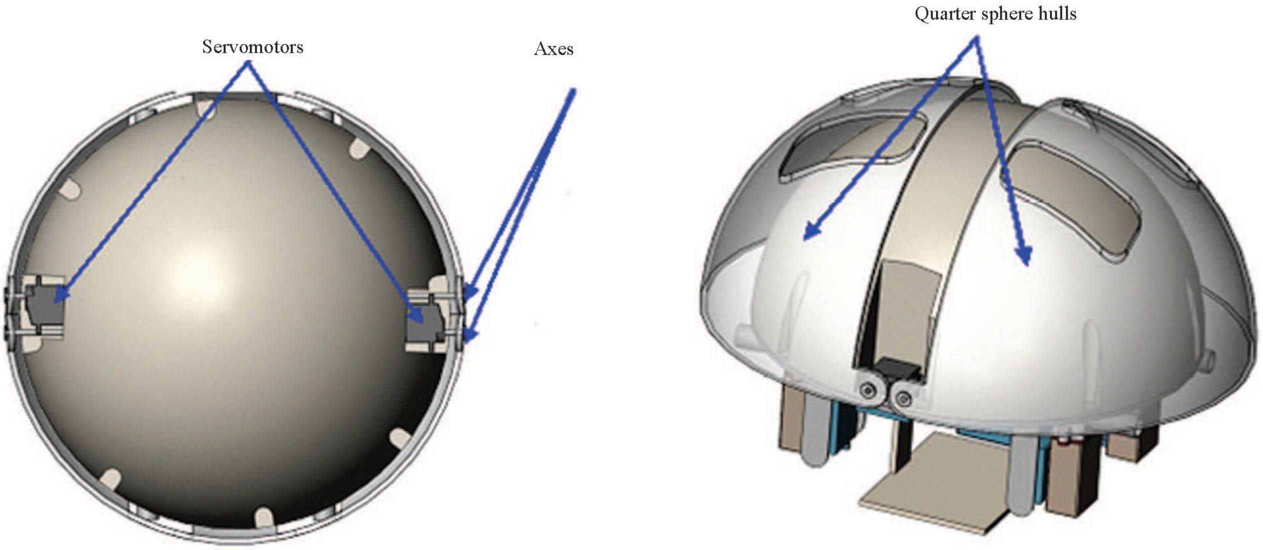
The quarter-spherical hulls are closed to maintain the spherical shape of the robot when it is actuated by the four water-jet propellers in water. The closed state offers several advantages. First, the two closed hulls protect the microrobots and the actuation system. Second, a spherical robot is relatively easy to rotate, with minimal water resistance and little disturbance to the surrounding underwater environment. Third, a spherical shape is not easily detected by sonar, and hence shows some potential for military applications.

2.3 Opening mechanism

Fig. 1 shows the opening mechanism of the mother robot. The diameter of the hemispherical upper hull is 234 mm, and the two quarter-spherical hulls each has a diameter of 250 mm. Each of the quarter-spherical hulls can rotate 90° around an axle fixed on the upper hemisphere. In the closed state, the centres of the two lower quarter-spherical hulls coincide with that of the upper hemispherical hull. The inner diameter of the quarter-spherical hulls is 10 mm larger than the outer diameter of the upper hemispherical hull. All three hulls have a thickness of 3 mm. The two lower hulls are respectively actuated by two servomotors along two rotational axes that are fixed in the upper hemisphere. The two rotational axes are separated by a distance of 20 mm, so the two quarter-spherical hulls can be controlled independently. Fig. 1b shows that the quarter-spherical hulls can be opened freely without colliding with the upper hemisphere.

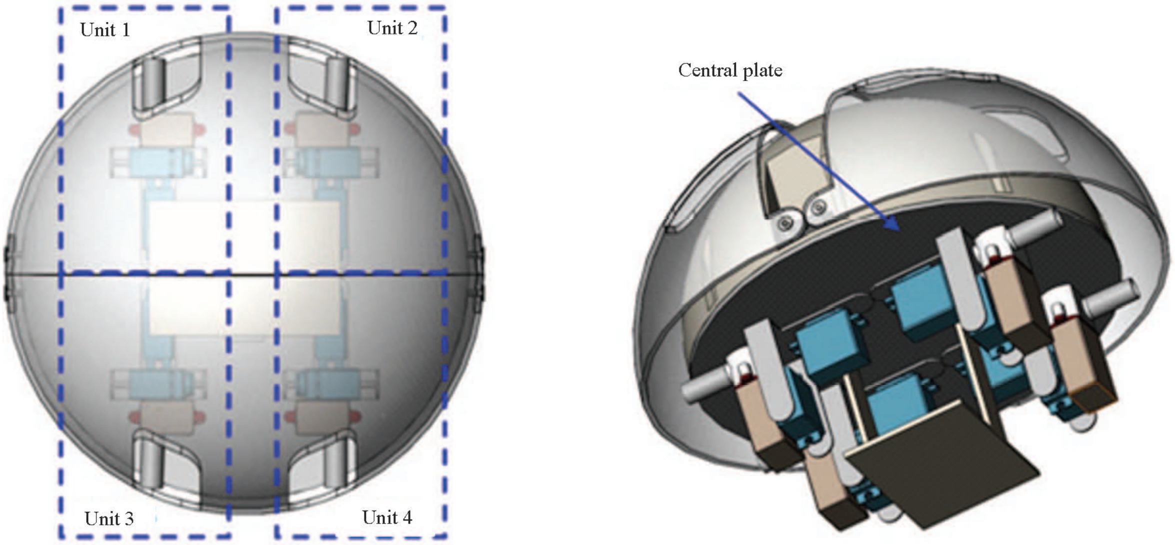
2.4 Actuating system

Fig. 2 shows the distribution of the four actuating units, which are installed symmetrically around the centre of the central plate. The four actuating units are suspended beneath the central plate by fixing the rotational axes of four servomotors, which are controlled independently. Each unit is composed of one carriage, one water-jet motor, and two servomotors. As shown in Fig. 2b, each unit has two DOFs, and an additional propulsive force can be generated by the water-jet motor in water. For the first generation of mother robots, we have chosen the servomotor JR DS3836, which has a compact size. Waterproofing is applied to the servomotors and water-jet motors. The mother robot can implement both multiple vectored water-jet-based cruising and quadruped walking via this actuating system.



(a) Top view (closed state) (b) Oblique view (opened state)

Fig. 1 Opening mechanism of the spherical robot.



(a) Bottom view (b) Oblique view

Fig. 2 Distribution of the four actuating units.

3 Amphibious motions

3.1 Walking motion

The proposed spherical robot can implement walking and rotating motions on land or seabed. First, the vertical servomotor rotates to lift up the water-jet propeller. Second, the horizontal servomotor actuates the water-jet propeller to swing forward. Third, the water-jet propeller is dropped down. Last, the water-jet propeller swings backward to implement one step.

A single actuating unit can implement forward motion via this step cycle. To implement quadruped walking of the whole robot, the timing sequence for the four actuating units must be designed to realise continuous walking. Different timing sequences result in different walking gaits. By changing the event sequence of the four legs, the robot can walk with different velocities. To achieve a stable walking motion, we chose the crawling gait, in which at least 3 legs are in contact with the ground. The time required for a single cycle was set at 1. Event sequences for different gaits are described by the dark and blank stripes. The time intervals when the legs are in contact with the ground (to support the robot) can be represents by the dark colour, while the time when the legs are off the ground can be indicated by the blank colour. The gait event sequence and its timing can be defined using the duty factor β. The duty factor for the crawling gait should fulfill $0.75 \leq \beta \leq 1$. When the duty factor is decreased from 0.75 to 0.5, the gait smoothly transfers from a singular crawl to a trot. At some instants, the robot relies on only two legs[38].

3.2 Underwater three-dimensional motions

The four water-jet propellers can rotate in the vertical and horizontal planes. By changing the directions and propulsive forces of these four vectored propellers, the robot can move forward or backward, rotate clockwise or counter-clockwise, surface or dive, and float in the underwater environment. Fig. 3 illustrates the underwater motions of the mother robot.

The four legs are denoted by letters A, B, C and D, as shown in Fig. 3d. Legs A and D function as one pair, and legs B and C as another pair. The robot can adjust one pair of water-jet propellers in the same horizontal direction to implement forward or backward motion in the horizontal plane, as shown in Figs. 3a and 3d. At the same time, it can use A-C or B-D to implement clockwise or counter-clockwise rotation around its geometrical centre, as shown in Figs. 3e and 3f. When necessary, it can turn left or right by simply changing the propulsive forces of two pairs of parallel propellers[39–41]. Additionally, the robot can adjust the four water-jet propellers in the vertical plane, generating vertical propulsive forces to implement surfacing/diving motions, as shown in Figs. 3b and 3d.

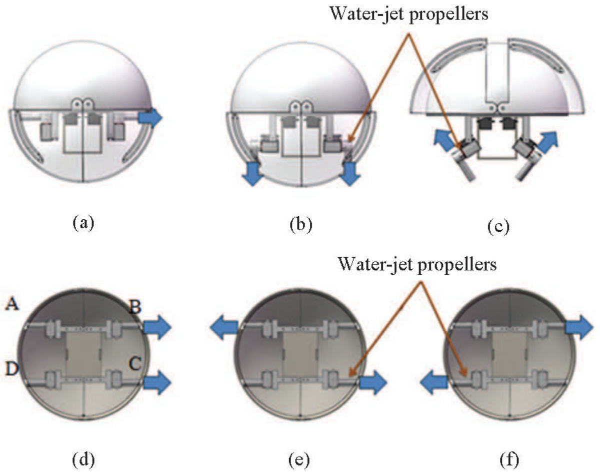


Fig. 3 Underwater motions[22]. Front view: (a) moving forward, (b) surfacing, (c) diving. Bottom view: (d) moving forward, (e) clockwise rotation, (f) counter-clockwise rotation.

4 Experiments

4.1 Prototype of the spherical mother robot

Fig. 4 shows the distribution of grooves on the profile of the upper hemispherical hull. Six small grooves were manufactured for bolts and nuts, and two large grooves were manufactured for the servomotors that open and close the two quarter-spherical hulls. The diameter of the upper hemisphere is 234 mm, and the two quarter-spherical hulls each have a diameter of 250 mm. Fig. 5 shows the two lower quarter-spherical hulls. Each lower hull of the water-jet propellers has two long holes, to be used while cruising or surfacing/diving in the closed state.

The actuating system includes four actuating units, which were installed on the central plate by fixing the rotational axes of the four vertical servomotors. The central plate has a diameter of 235 mm, and was installed beneath the upper hemispherical hull. For the sake of compactness, we chose the Power100 motor Raboesch as the water-jet propeller, and used JR DS3836 servomotors to implement rotation in the horizontal and vertical directions. A single servomotor has dimensions

$21.5 \times 21.5 \times 11$ mm^3, and it is capable of rotating 120°, and provides a maximal torque of 2 kg·cm. The dimensions of the water-jet motor without the nozzle are $21 \times 31 \times 46$ mm^3. Each water-jet motor was sealed in a waterproof box, and the waterproofing design was also applied to all servomotors. Four motor carriages were fabricated from stainless steel with a large degree of bending stiffness.

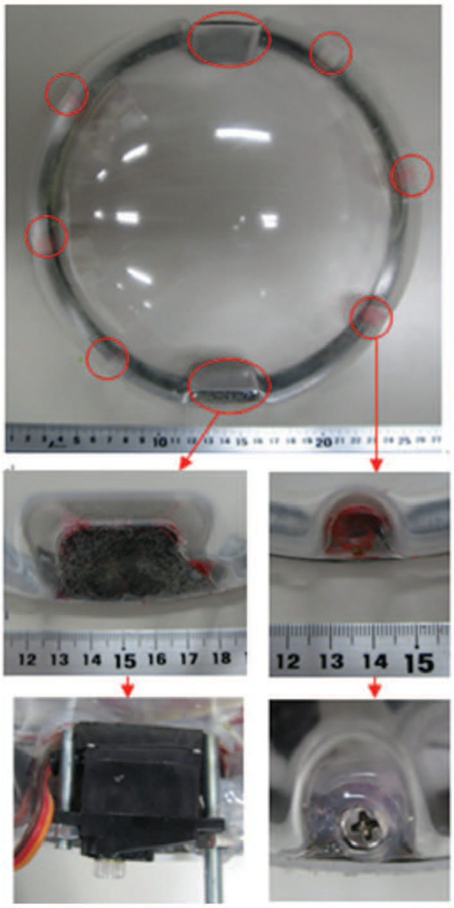


Fig. 4 Groove distribution of the upper hemispherical hull.

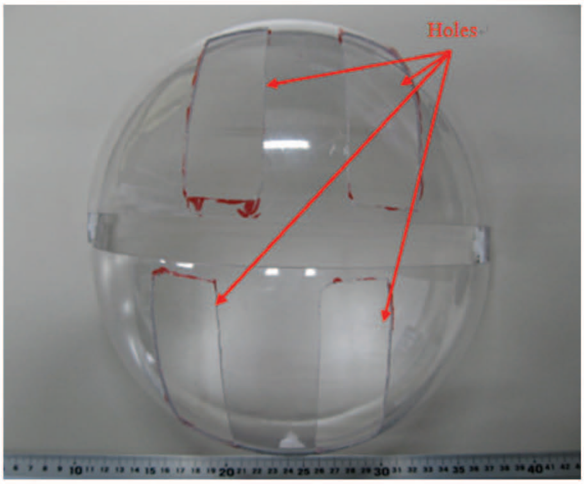
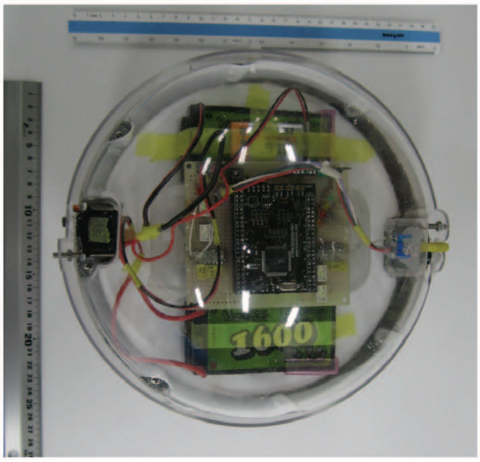
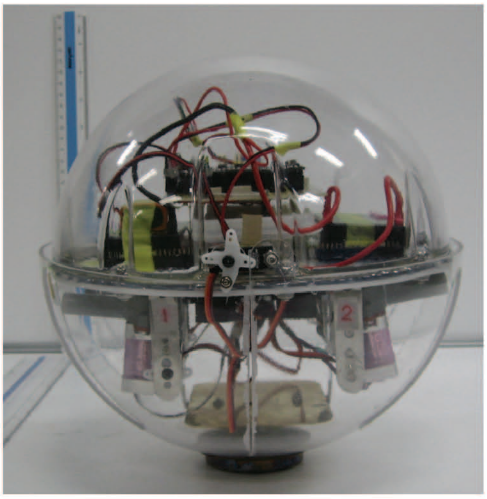


Fig. 5 Lower quarter-spherical hull holes.

Fig. 6 shows the prototype of the spherical mother robot. The total mass of the prototype robot is about 1.41 kg. We selected the ATmega2560 as the microprocessor unit. Six distance sensors were installed symmetrically around the horizontal circumference, and a single pressure sensor was fixed underneath the central plate. All sensor signals were transmitted to an AD conversion board, which converted them to digital values and communicated with the microprocessor through the serial port. The microprocessor unit, motor-driving circuits, and power supply were fixed and sealed inside the upper hemisphere.



(a) Top view



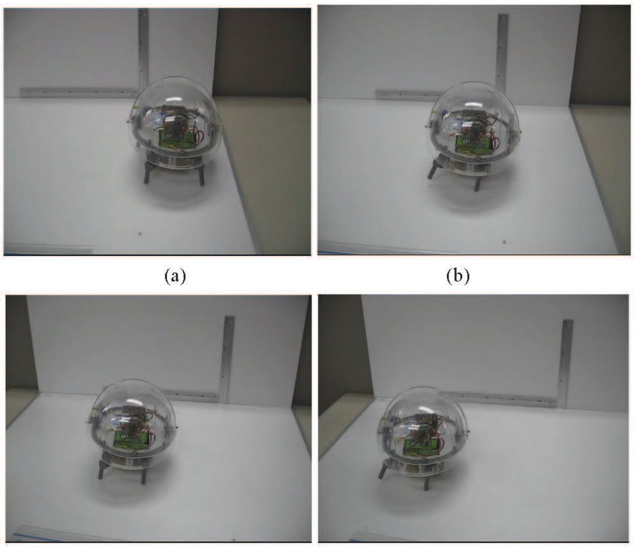
(b) Left view

Fig. 6 Prototype of the spherical mother robot.

4.2 Walking motion

We carried out the walking experiment on a flat floor. The robot's crawling gait (a stable, regular, symmetric gait) was inspired by the walking motion of an amphibious turtle. In the crawling gait, a raised leg is set down before the next one is lifted. At some instants in each step cycle, the robot relies on only two legs[38].

Fig. 7 shows a video sequence of the walking motion on the flat floor. To implement stable walking, we reduced the swing distance for a single step. We recorded the time and displacement in the walking experiment, and calculated the average walking speeds. Fig. 8 presents the experimental results. The alternating swing and lifting motions generated some differences in the average walking speeds.


(a) (b)

(c) (d)

Fig. 7 Walking motion.

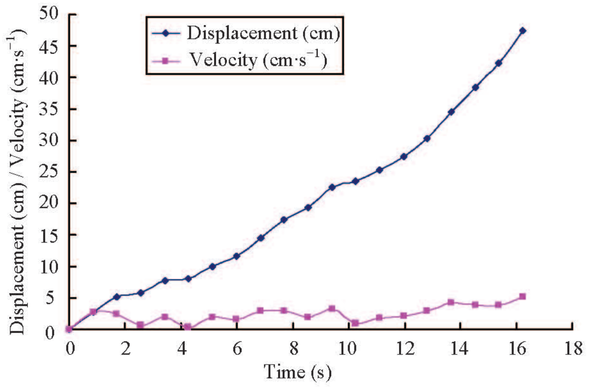


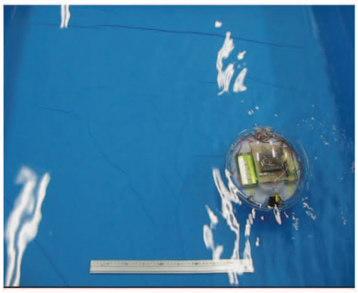
Fig. 8 Experimental walking speed results.

4.3 Underwater motions

We also carried out experiments to evaluate the underwater motions of the robot. Fig. 9 shows a video sequence of the horizontal forward motion, in which one pair of water-jet propellers provided the same propulsive forces. We recorded the time and displacement in the forward motion experiment, and calculated the average speeds. Fig. 10 presents the experimental results. The horizontal speeds were relatively stable.

By changing the propulsive forces of a pair of vectored propellers, the robot can turn left or right with different turning radii. Fig. 11 shows a video sequence of the left turn experiment. First the robot moved forward along the *X*-axis, then executed a left turn, and finally moved forward along the *Y*-axis. We recorded the *X*- and *Y*-coordinates of its geometric centre. Fig. 12 presents the experimental trajectory results for the left turn.

Fig. 13 shows a video sequence of the right turn experiment. First the robot moved forward along the *X*-axis, then executed a right turn, and finally moved forward along the *Y*-axis. We recorded the *X*- and *Y*-coordinates of its geometric centre. Fig. 14 presents the experimental trajectory results for the right turn.


(a) Initial position

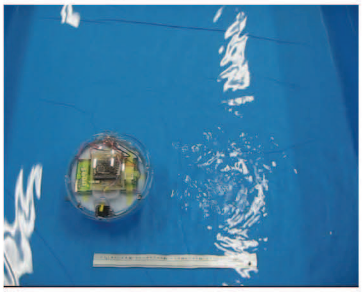

(b) Final position

Fig. 9 Underwater horizontal motion (moving forward).

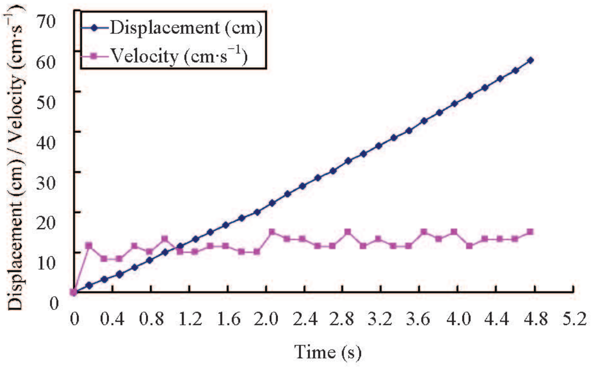
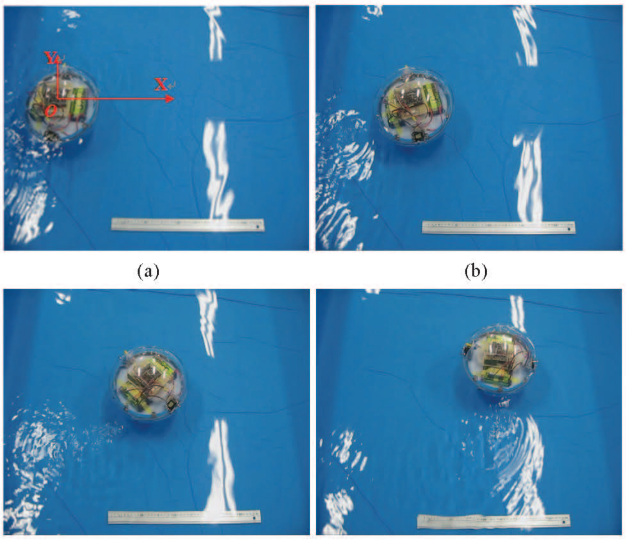


Fig. 10 Experimental speed results for horizontal forward motion.



(a) (b)

(c) (d)

Fig. 11 Underwater horizontal motion (left turn).

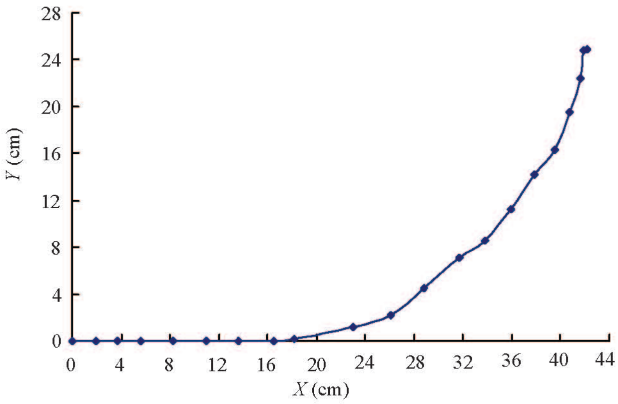
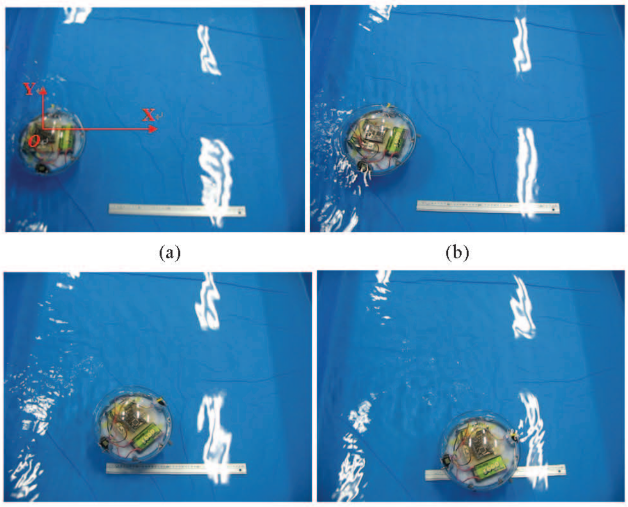


Fig. 12 Experimental trajectory results for horizontal motion(left turn).



(a) (b)

(c) (d)

Fig. 13 Underwater horizontal motion (right turn).

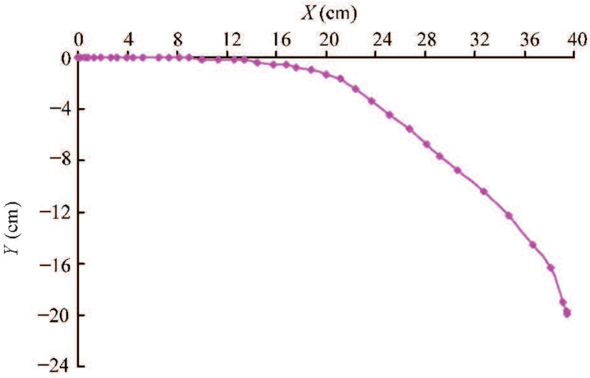
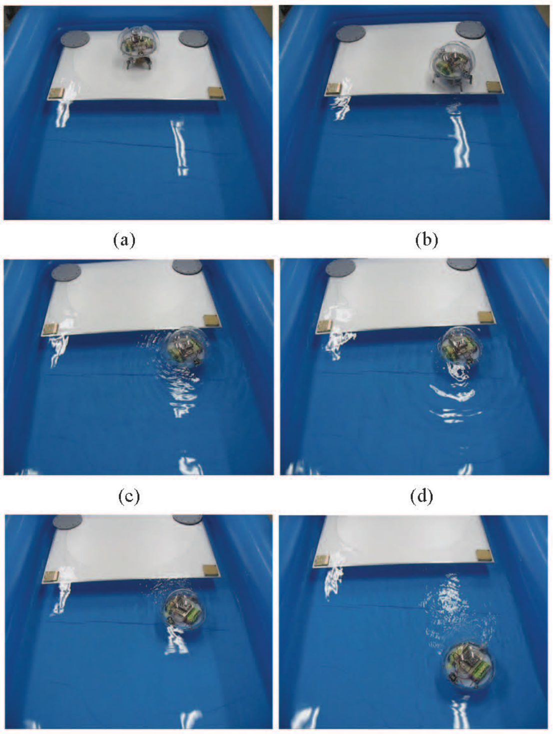


Fig. 14 Experimental trajectory results for horizontal motion (right turn).

4.4 Amphibious motions

The amphibious motions were also implemented in a large water tank. First, the robot walked forward on a white board. When it was close to the edge of the board, it jumped into the water tank by taking a large step. Next, it folded its four legs inside the two quarter-spherical hulls, which were then closed. Finally, it adjusted two water-jet propellers in the same horizontal direction. The robot was then actuated by these two parallel water-jet propellers to move forward. Fig. 15 shows a video sequence of this hybrid motion.



(a) (b)

(c) (d)

(e) (f)

Fig. 15 Amphibious motion: (a) initial position; (b) walking forward; (c) jumping into the water; (d) folding the four legs and closing the two quarter-spherical hulls; (e) forward motion of the robot actuated by two water-jet propellers; (f) final position.

5 Conclusion

To overcome the problems confronting previously developed microrobots in real-world applications, in this paper we proposed a mother-son robot system, composed of several microrobots as sons and a newly designed amphibious spherical robot as the mother. The mother robot possesses the attributes of long endurance, stable high speed, and large load capacity. Inspired by amphibious turtles, the mother robot was designed with a spherical body and four legs. It is actuated by four water-jet propellers and eight servomotors, and it is capable of a walking motion on land and tri-directional motions in an underwater environment. We fabricated a prototype of this amphibious spherical robot and evaluated its walking motion on land. Forward and turning motions were implemented in a water tank. This paper presented the experimental results. Finally, we carried out an amphibious experiment, in which the robot walked from ‘land’ into water using four legs, and then moved forward in the water using two parallel water-jet propellers. Good motion performance was observed in the experiment.

In future work, we will evaluate the surfacing and diving motions of the robot in a deep swimming pool. We will also install additional sensors to enable more stable control. We will then use this amphibious spherical mother robot to carry developed microrobots to a target position.

Acknowledgments

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