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# Skating Motion Analysis of the Amphibious Quadruped Mother Robot

Liwei Shi[1], Yanlin He[1], Shuxiang Guo[1, 2]
[1]School of Life Science, Beijing Institute of Technology, Haidian District, Beijing, China
[2]Faculty of Engineering, Kagawa University, 2217-20 Hayashi-cho, Takamatsu, Kagawa, Japan
slw8304@hotmail.com, 843734173@qq.com, guo@eng.kagawa-u.ac.jp

***Abstract* - Biomimetic underwater robots are of great interest for underwater monitoring operations, such as pollution detection and video mapping. However, in some restricted underwater environments, regular sized robots are not suitable for real applications. Therefore, 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, for real-world applications, they lacked the attributes of long endurance, high stable speed, and large load capacity. To implement these characteristics, we proposed a mother–son robot system, which includes several microrobots as sons and a newly designed amphibious spherical robot as the mother. Inspired by the amphibious turtle, the mother robot was designed with a spherical body and four legs. It was actuated by four water-jet propellers and ten servomotors, capable of walking motion on land and three directional moving motions in the underwater environment. We developed a prototype of the amphibious spherical robot and evaluated its walking and swimming motions experimentally. To improve the walking velocity on level or comparatively smooth terrain, we added four passive wheels on four legs with lightweight. The skating trajectory was investigated to implement high terrain adaptability of the mother robot.**

***Index Terms – Amphibious Quadruped Robot, Mother-son robot system, Biomimetic robot, Spherical robot.***

## I. INTRODUCTION

Underwater robots have been widely used to implement underwater tasks that humans deem dangerous, dull and dirty. This is mostly due to their ability of multi-functionality, flexibility, and high accuracy. This trend has continued into underwater monitoring operations including pollution detection, video mapping, exploration of unstructured underwater environments, and other tasks [1–2].

In recent years, many types of underwater robots, which were designed with streamlined structures to pursue high-speed cruising, have been reported. While the use 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 have also been introduced [3]. A multi-channel Hall-effect thruster has also been reported, involving vector composition of underwater robots [4]. Moreover, we have developed a spherical underwater robot equipped with three vectored water-jet-based thrusters [5].

Various configurations, shapes, and sizes of underwater robots are required for different applications or tasks. For underwater environmental detection or observation, a compact structure with multi-functionality and flexibility enables a robot to work in limited spaces. When a large range of motions and large load capacity are required, a traditional motor-actuated electromagnetic structure is essential. When large interior space and flexible multidirectional rotation in a restricted space are required, a spherical robot body is recommended. When high-speed cruising is required, a streamlined robotic body may be the best choice [6].

To be used in very complicated underwater environments such as narrow pipelines or a region filled with reefs, an underwater robot should possess the attributes of endurance, stable high speed, large load capacity, flexibility, compact structure and multi-functionality. To implement these characteristics, we proposed a mother-son robot system, which included several microrobots as sons and a newly designed amphibious spherical robot as the mother [7–8]. When the mother robot reaches the desired location, or encounters a narrow channel that is difficult to get across, it assumes a stable position and acts as a base station for the microrobots. Then, the microrobots exit the mother robot, proceed to the target position, and carry out their tasks.

Firstly, we designed several novel types of underwater microrobots, inspired by various insects and marine animals, using ionic polymer metal composite (IPMC) and shape memory alloy (SMA) actuators [9–12]. These microrobots possessed some of the attributes of compact structure, multi-functionality, flexibility, and precise positioning. The developments and experiments of these microrobots have been introduced in the previous work. So, here we will not repeat it again. In this paper, we would focus on the regular-sized mother robot. Then, inspired by amphibious turtles, the mother robot was designed to have a spherical body and four legs. For the mother robot is to be used in limited underwater environments, so it should be endowed with the combined attributes of endurance, stable speed, large load capability, flexibility, and compact structure. The traditional streamlined shape does not possess a compact structure and maximum interior space. Also, it is hard to rotate in limited spaces with a streamlined shape. ACM series snake-like robots and amphibot are all snake-like robots with the long streamlined shapes [13–14]. Amphibious Rhex is a six-legged robot, which just use six legs to push water when it is swimming in water. The efficiency of this propulsive mechanism is not high in water. Also, it is hard to implement vertical floating motion in water by using these six legs to push water, which will restrict its flexibility [15].

Inspired by amphibious turtles, the mother robot was designed to have a spherical body and four legs. A spherical body had both a compact structure and maximum interior space, compared to a streamlined body. It could rotate and change direction more easily than a streamlined design, which was very important for microrobots in restricted spaces. Also, the robot was actuated by using vectored water-jet propellers, which could be controlled easily with a stable thrust. In addition, this kind of actuation could generate little vortex, and it was silent and environment friendly. To expand the range of motion of the overall system, we designed the mother robot for amphibious use, which was capable of a walking motion on land and tri-directional cruising motions in an underwater environment. To implement high terrain adaptability, the mother robot was improved to skate on level or comparatively smooth terrain with four passive wheels.

The remainder of this paper is divided into four parts. First, we propose the mother-son robot system and describe the feasibility results for several previously developed microrobots. Second, inspired by the amphibious turtle, we introduce a new type of spherical mother robot with one hemisphere, two quarter spheres, and four legs, which can implement amphibious motions. Third, we discuss the development of a prototype of this underwater robot, together with a series of experiments to evaluate its walking motion on land, surging motion in the horizontal plane, and turning motion. Fourth, we improve the mother robot to skate with four passive wheels and investigate its skating trajectory on level or comparatively smooth terrain. Finally, we present our conclusions.

## II. Mother-son Robot System

### A. Mother-son Robot System

Underwater microrobots possess some attributes of compact structure, multi-functionality, flexibility, and precise positioning, which can be used in limited underwater environments. However, they lack the attributes of long endurance, stable high speed, and large load capacity. To implement these characteristics, we proposed a mother–son robot system, which included several microrobots as sons and a newly designed amphibious spherical robot as the mother. The mother robot can carry son microrobots to be close to the target position and release these microrobots.

Compared with a single large robot, when the final tasks are carried out by microrobots, it is easier to adapt to narrow environments and implement relatively high positioning precision. Also, compared with individual microrobots, the mother–son system offers the following advantages.

(1) The motion range of the overall system is expanded, owing to the relatively high speed and endurance of the mother robot.
(2) The microrobots can obtain a relatively stable, high power supply from the mother robot.
(3) Since the microrobots are all controlled by the mother robot, communications between microrobots can be implemented by the mother when cooperation is needed.
(4) Since the power supply and control units are installed in the mother robot, the microrobots can be designed with a more compact structure, suitable for restricted spaces such as narrow pipelines or channels.

### B. Review of Previously Developed Microrobots

Based on stick-insect-inspired walking locomotion, a prototype of an eight-legged microrobot was developed by using IPMC actuators [1]. It was 33 mm long, 56 mm wide, and 9 mm high. Four legs were used as drivers, and the other four actuators were used as supporters. It was capable of walking, rotating, and diving/surfacing. However, the floating efficiency of this microrobot was not high. To improve the floating motion, a prototype of a jellyfish-type microrobot was constructed by using SMA and IPMC actuators, based on jellyfish-inspired locomotion [1]. It was 68 mm high, with a weight of 4.81 g in air. This biomimetic microrobot consisted of a two-ring body and four legs. The body was designed to imitate a jellyfish’s diving/surfacing motions. Additionally, four IPMC actuators were fixed on the body to implement walking motion in two directions. Although the floating motion was improved, the prototype was unable to rotate, and the walking motion was unsatisfactory because the center of gravity was located in one of the two halves of the body, causing an imbalance in the overall body and a large amount of slippage.

For the purpose of creating a microrobot with a compact structure and multi-functions, an inchworm-inspired microrobot with ten IPMC actuators was developed. It was 33 mm long, 14 mm wide, and 14 mm high. Four outside actuators were used as legs to implement walking, rotating, and floating motions. The other six actuators were used as fingers to grasp small objects [10]. Compared with the jellyfish-like robot, this design offered the advantages of stability, compact structure, less water resistance, and grasping motion implementation. However, because the rotating radii were not same for the outside four legs, a large amount of slippage occurred while rotating, and the rotating efficiency was not high. Only the outside four legs were used to electrolyze the water around the IPMC surface, generating air bubbles, which became attached to the surfaces of the legs, increasing the buoyancy and implementing the floating motion. Due to the limitations of the structure, the inside six legs were used solely as fingers to grasp an object.

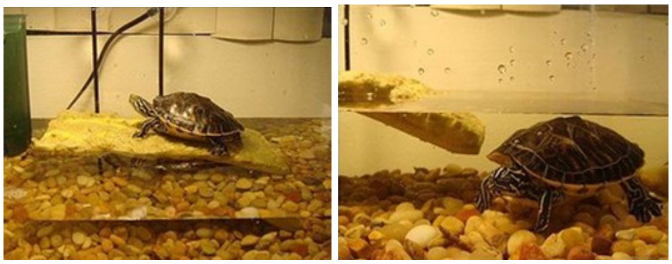
## III. Amphibious Spherical Mother Robot

### A. Biomimetic Locomotion

Nature provides perfect models for robots. Biomimetic robots borrow their senses and structure from animals, such as insects, fish, and birds. Turtles are reptiles of the order Testudines characterised by a special bony or cartilaginous shell developed from their ribs that acts as a shield. Figure 1 shows the photographs of a living amphibious turtle. The upper shell of the turtle is called the carapace, while the lower shell that encases the belly is called the plastron. The carapace and plastron are joined together on the turtle's sides by bony structures called bridges. The amphibious turtles normally have four feet, which are webbed and often have long claws.

They can walk on land or along the bottom of the river and lake. While swimming underwater, these turtles use all four feet in a way similar to the dog paddle. Four feet on the left and right side of the body alternately provide thrust [16].

Inspired by the amphibious turtle, the mother robot was designed with a spherical body and four legs, which possesses amphibious motions and extends the motion range of the son microrobots. The spherical structure can rotate and change its direction more easily than the traditional streamlined structure and possesses relatively large inner space for microrobots.



(a) (b)

Fig. 1 Photographs of a living amphibious turtle [17]. (a) on land, (b) in water.

### B. *Proposed Spherical Structure*

Figures 2 shows the opening state of the proposed amphibious spherical robot, which is composed of one hemisphere, two quarter spherical hulls, and four legs. Each leg is actuated by two servomotors and one water-jet propeller, in which two servomotors are perpendicularly installed in the horizontal plane and the vertical plane respectively. Each water-jet propeller can be rotated by the two servomotors, and hence the direction of the jetted water can be changed in the horizontal plane and the vertical plane, either respectively or simultaneously. Two quarter spherical hulls are actuated by another two servomotors, which can implement opening and closing motion. Figure 3 shows the closing state of the proposed spherical robot.

### C. *Mechanism of Walking Motion*

The proposed spherical robot can implement walking motion and rotating motion on land. Figure 4 shows one step circle of one leg while walking. First, 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, it swings backward to implement one step. By changing the gait of four legs, the proposed robot can walk and rotate with different velocities.

### D. *Mechanism of Underwater Three Dimensional Motions*

Four water-jet propellers can rotate in the vertical and horizontal planes. By changing the directions and propulsive forces of four vectored propellers, it can move forward and backward, rotate clockwise and counter-clockwise, surface/diving, and suspend in the underwater environment. Figure 5 shows the underwater motions of the proposed mother robot.

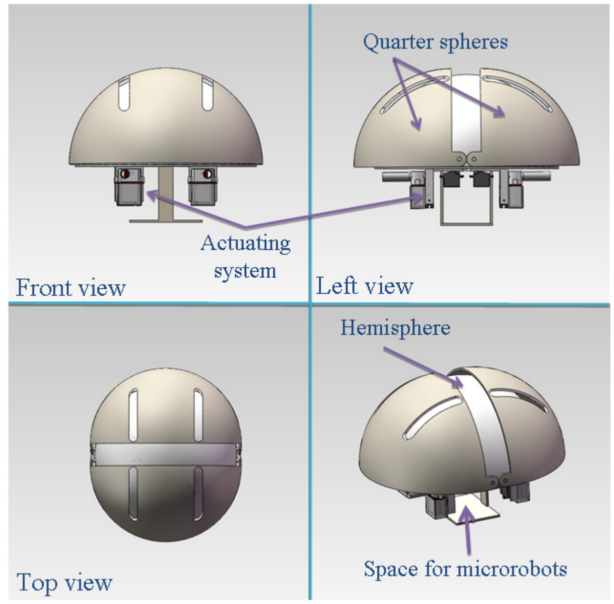



Fig. 2 Proposed mother robot (Opening state)

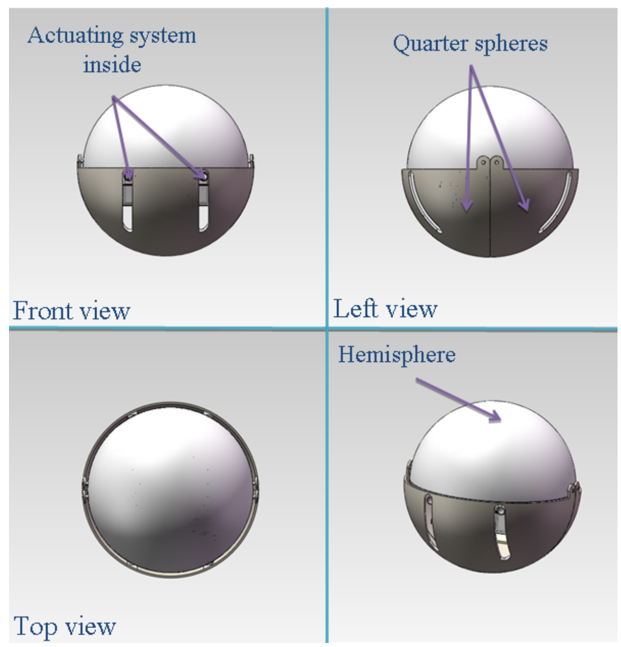



Fig. 3 Proposed mother robot (Closing state)

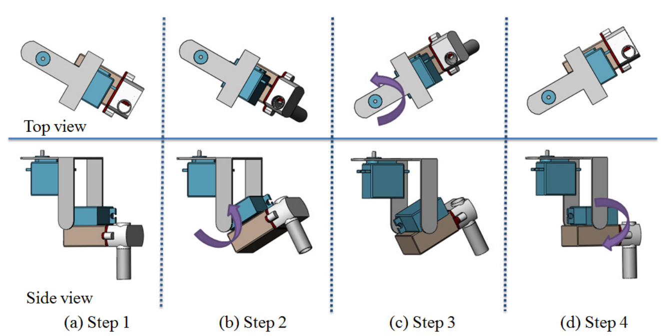



Fig. 4 Walking motion for one leg. (a) Lift up, (b) Swing forward, (c) Drop down, (d) Swing backward.

Four legs are defined from A to D, as shown in Fig. 5 (d). Legs A-D compose one pair, and legs B-C compose another pair. The robot can adjust one pair of water-jet propellers along a horizontal parallel direction to implement forward or backward motion in the horizontal plane, as shown in Fig. 5 (a) and (d). Meanwhile, it can use A-C or B-D to implement rotating clockwise or counter-clockwise around its geometry center, as shown in Fig. 5 (e) and (f). When it is needed, it can turn left or right by only changing propulsive forces two pair of parallel propellers. In addition, the robot can adjust four water-jet propellers in the vertical plane, which can generate vertical propulsive forces to implement surfacing/diving motions, as shown in Fig. 5 (b) and (d).

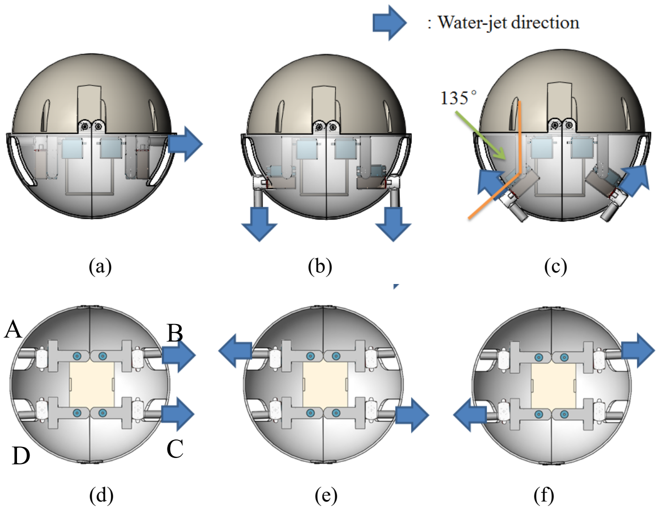



Fig. 5 Underwater motions. Front view: (a) Moving forward, (b) Surfacing, (c) Diving; Top view: (d) Moving forward, (e) Clockwise rotation, (f) Counter-clockwise rotation.

## IV. Prototype Spherical Mother Robot

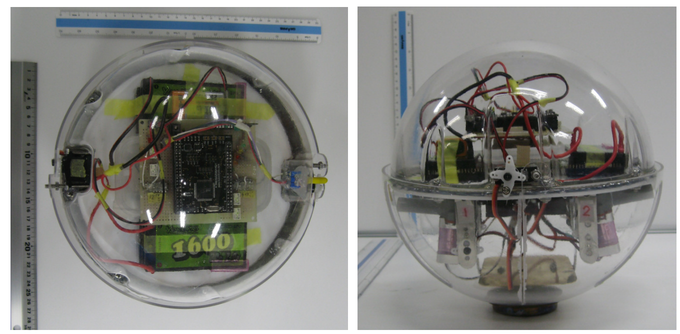
### *A. Prototype Spherical Mother Robot*

Figure 6 shows the prototype spherical mother robot. It is consists of one hemisphere body, two quarter spherical hulls, and four legs with two DOFs. The diameter of the upper hemisphere was 234 mm, and the diameters of two quarter spherical hulls were 250 mm. The thicknesses of the upper hemisphere and two quarter spherical hulls are same with 3 mm. Figure 7 shows the grooves distribution on the profile of the upper hemisphere. Six small grooves are manufactured to install bolts and nuts, and two large grooves are also manufactured to install the servomotors for the opening motion of two quarter spherical hulls. The total weight of the prototype robot is about 1.41 kg. We used an ATmega2560 as the microprocessor unit. The microprocessor unit, motor-driving circuits, and power supply were fixed and sealed in the upper hemisphere.

### *B. Walking Motion*

We carried out the walking experiments on the flat floor. One step circle of each leg is shown in Fig. 4. Inspired by the walking motion of an amphibious turtle, the robot adopted the crawl gait, which was a statically stable regular symmetric gait. In the crawl gait, one leg in the air was set down before the next one was lifted [18].

The walking gait (duty=75%) of four legs is shown in Fig. 10. Figure 11 shows the video sequence of the walking motion on the flat floor. To implement a stable walking, we reduced the swing distance for one step. We recorded the times and displacements in the walking experiment and calculated the average walking speeds. The experimental results are shown in Fig. 12. For the swing and lifting motions alternately appeared, some differences were generated for the average walking speeds.



(a) Top view (b) Left view

Fig. 6 Prototype spherical mother robot

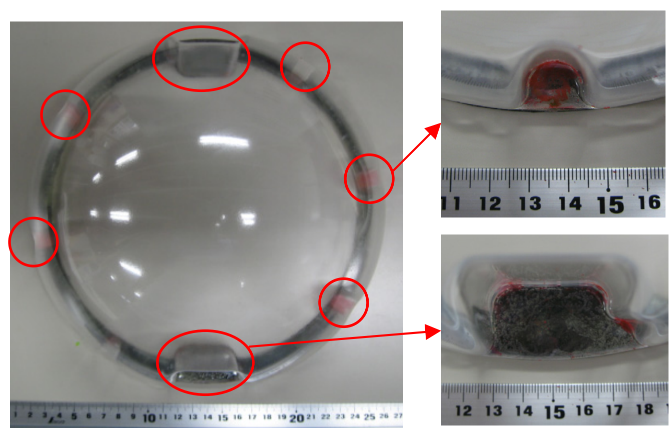


Fig. 7 Grooves distribution

## V. Skating Motion

### *A. Structure Improvement*

The quadruped walking motion on land can select discrete foot points with multi-articulated legs, which has a high efficiency and is stable even on rugged terrain. On the even terrain, the wheeled locomotion is more efficient than the walking motion. To increase the terrain adaptability and improve the walking velocity on level or comparatively smooth terrain of the developed mother robot, we added four passive wheels on four legs to implement skating motion without additional motors. Figure 8 show the proposed structure of the improved quadruped mother robot. Four passive wheels were installed at the ends of four water-jet propellers, which could increase a hybrid motion on land with lightweight. The proposed actuating system is shown in Fig. 9. Each passive wheel can be actuated to swing cyclically along two perpendicular axes by two servomotors.

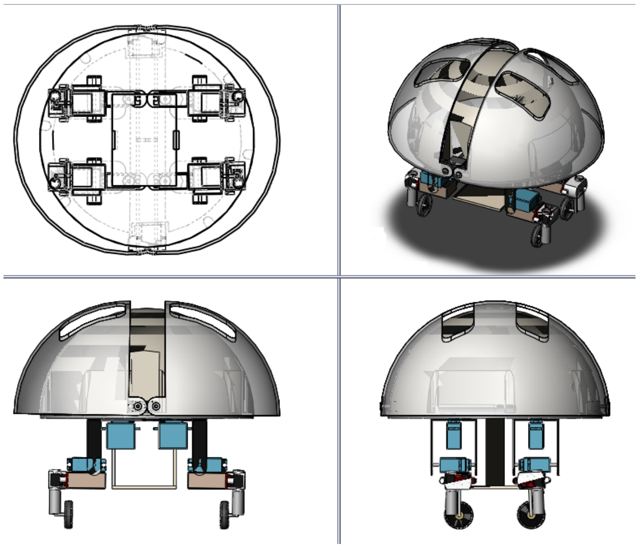


Fig. 8 Improved structure with four passive wheels

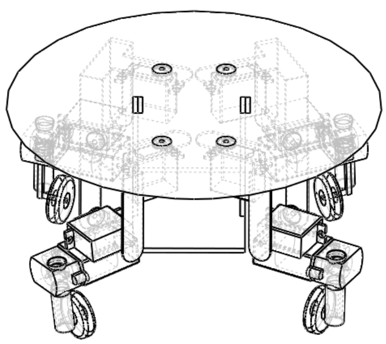


Fig. 9 Proposed actuating system

### *B. Skating Mechanism*

In the legs' working space, there are an infinite number of possible trajectories [19]. To implement high stability, easy analysis and independence from payload, several assumptions have been made by Endo et al. in [20]. In the skating process, four legs should be on the ground and each leg produces cyclic motion on a fixed motion.

For the straight skating motion, two front legs or two hinder legs implement a symmetric motion. In our proposed structure each leg had two joints, which could swing along X and Y axes, as shown in Fig. 10. The cyclic trajectory can be fixed by the amplitudes and frequency of the prismatic motion and swing motion of each leg. For the symmetry, the transverse reaction forces can be counteracted between two front legs or two hinder legs. Therefore, the longitudinal forces will be left as the driving force to skate. We used the sine wave to describe the position of the wheel along $X$ and $Y$ axes respectively, as shown in Equations (1) and (2).

$$A(t) = -A_{offset} + A_m \left[ \sin\left(\frac{2\pi}{T}t + \frac{3}{2}\pi\right) \right] \tag{1}$$

$$\theta(t) = \theta_m \sin\left(\frac{2\pi}{T}t + \frac{3}{2}\pi + \varphi\right) \tag{2}$$

where $A_{offset}$ denotes the offset of the wheel from the nozzle centre in skating locomotion, $A_m$ denotes the maximal amplitude along X axis, $\theta_m$ is the maximal amplitude of the swing angle, and $\varphi$ is phase difference between $A(t)$ and $\theta(t)$. $\frac{2\pi}{T}$ denotes the frequency of the cyclical motion.

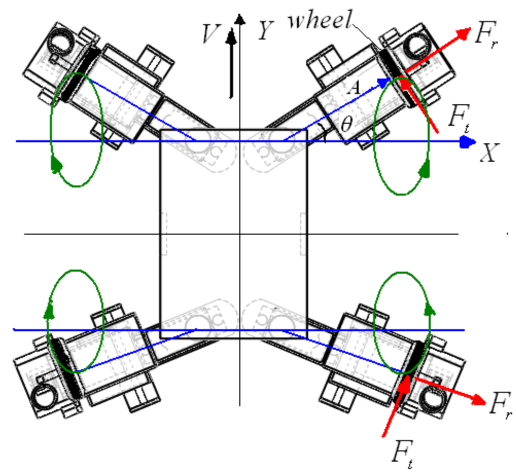



Fig. 10 Body coordinates and cyclic trajectory in straight motion

For the angular skating motion, two pair diagonal legs implement a symmetric motion, the reaction force along radius can be counteracted. Therefore, the angular forces will be left as the driving force to skate. The cyclic trajectory can be fixed by the amplitudes of the prismatic motion and swing motion of each leg, as shown in Fig. 11.

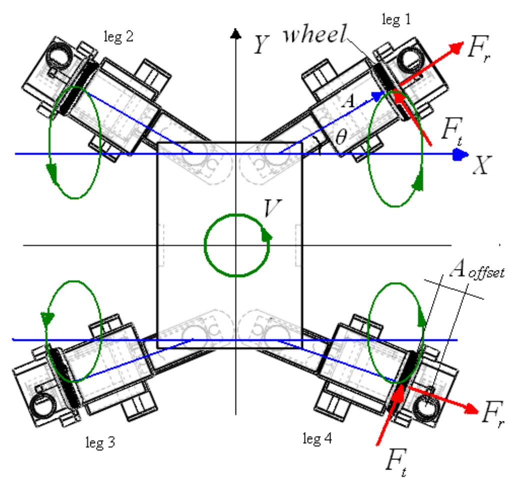



Fig. 11 Cyclic trajectory in angular motion

### *C. Prototype Actuating System with Passive Wheels*

Figure 12 shows the prototype actuating system for the skating locomotion. We have implemented some test experiments on the flat desk. The motion efficiency is low for the camber angle is not perpendicular to the ground. The angle change mechanism should be improved to adjust the angle automatically when the leg swings.

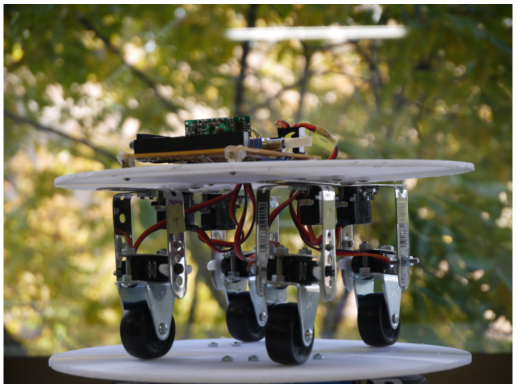


Fig. 12 Prototype actuating system

## VI. CONCLUSIONS

In this paper, to conquer the problems of previous developed microrobots in real applications, we proposed a mother–son robot system, which included 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 the amphibious turtle, the mother robot was designed with a spherical body and four legs. It was actuated by four water-jet propellers and eight servomotors, capable of walking on land and three directional moving in the underwater environment. We developed a prototype of the amphibious spherical robot and evaluated its amphbious motions. To implement high terrain adaptability, the mother robot was improved to skate on level or comparatively smooth terrain with four passive wheels. We designed the conceptual structure of the improved robot and analysis the straight and angular motions of the skating model.

For the future work, we will evaluate and optimize the skating motion experimentally.

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