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Experimental Study on Drag-induced Balancing via a Static Tail for Water-running Robots

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Abstract

Robotics is one area of research in which bio-inspiration is an effective way to design a system by investigating the working principles of nature. Recently, tails have received interest in robotics to increase stability and maneuverability. In this study, we investigated the effectiveness of a static tail for bio-inspired water-running locomotion. The tail was added to increase the stability in the rolling and yawing directions based on the hydrodynamic force from interaction between the tail and the water. The drag coefficient in the interaction is not easy to calculate analytically, so experimental studies were done for various static tail shapes. Five different shapes and compliances in two directions were considered for experimental design candidates. The result was applied to design a stable amphibious robot that can run on ground and water surfaces.

Keywords: bio-inspiration, water-running robot, static tail, stability, hydrodynamic balancing, basilisk lizard

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1 Introduction

Bio-inspiration is used for designing engineering systems based on working principles of nature[1]. Since bio-systems are optimized for their environments, researchers can gain much knowledge by studying their structures and mechanisms. A cheetah-inspired robot[2], BigDog[3], and RHex[4] are well-known bio-inspired legged robots that are made to run on the ground. Stickybot[5] and RiSE[6] are well-known lizard-inspired robots used for climbing. Many bio-inspired products have also been commercialized, such as Velcro[7] and shark-inspired low-drag swimming suits[8].

Results of bio-robotics research are effectively used to design and control engineering systems. Recently, the DARPA robotics challenge was held to test humanoid robots in nuclear accidents[9]. Gecko-inspired climbing robots are very useful for cleaning or exploring high-rise buildings[10]. Cheetah robots were recently developed to achieve high speeds faster than that capable by human beings[11,12]. Insects such as cockroaches have also been studied for their locomotive and sensing abilities[1,13].

The basilisk lizard can run on water using impact and drag forces. By fast cyclic motion of the footpads, the lizard can run on water surface with high speed. Many researchers have tried to develop robotic platforms inspired by basilisk lizard. Floyd and Sitti[14] developed a quadruped robotic platform based on four-bar linkage mechanisms. Xu *et al*.[15] designed a biped water-running robot. They used a Watt-I mechanism to mimic the footpad path of basilisk lizards. Kim *et al*.[16] developed a hexapedal robot to run on ground and water surfaces. The robot had two important characteristics in its design: spherical footpads to use drag and buoyancy forces simultaneously, and a Klann mechanism for a stable footpad path. All of these platforms presented sufficient lifting force to run on water surface, but more research is required to develop a reliable robotic platform for stable and agile locomotion.

In investigations of bio-systems, tails have proven to be very effective in increasing stability and maneuverability during locomotion. Briggs *et al*.[17] tried to counteract disturbance moments via tail movement during high-speed locomotion. Libby *et al*.[18] investigated the function of a lizard tail during jumping and developed a robotic platform for pitch control in the air.

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Zhao et *al*.[19] developed a jumping robot that can be controlled while in the air. Kohut *et al*.[20] achieved fast steering with a cockroach-inspired robot by using a tail. They used the aerodynamic force from the light-weight tail in steering, and a small weight was added to implement the steering mechanism.

Several studies were also performed to improve the performance of water-running robots. Park *et al*.[21] introduced a vertically movable tail to compensate for the pitching moment induced by the repeated motion of the footpads. Feedback control was used to maintain the pitching angle at zero, and simulation was performed. Kim *et al*.[22] proposed a horizontally movable tail to compensate for the rolling moment of water-running robots. The strategy was different from that by Park *et al*.[21] in that the tail moves in a cycle with synchronized motion with the footpads. Both studies showed good performance, but the feedback control was not easy to implement, and the cyclic motion consumed too much energy.

This study proposes a bio-inspired static tail to improve the stability of a water-running robot. A static tail has advantages that no control or additional energy is required during the operations. Hydrodynamic force from the interaction between the static tail and water is used to compensate for the rolling and yawing moments induced by repeated motion of the footpads. Several candidate shapes and compliances for the tails were empirically tested to find the optimal parameters.

The rest of the paper is organized as follows. Section **2** introduces the principle of the static tail during water running and the forces generated from the footpads and the tail. Section **3** introduces the design parameters of the tail with different shapes and compliances. Section **4** presents the experimental results, and section **5** summarizes the conclusions.

2 Tail: bio-inspiration and analysis

2.1 Function of a tail during water running

The posture of a basilisk lizard running on water is shown in Fig. 1a, and a schematic is shown in Fig. 1b. The fast footpad locomotion generates an air cavity based on the drag force from the water surface. The lizard generates sufficient vertical drag force to maintain the position over the water surface, and the horizontal drag force generates a thrusting force to move the robot forward. From these forces, imbalance eventually occurs

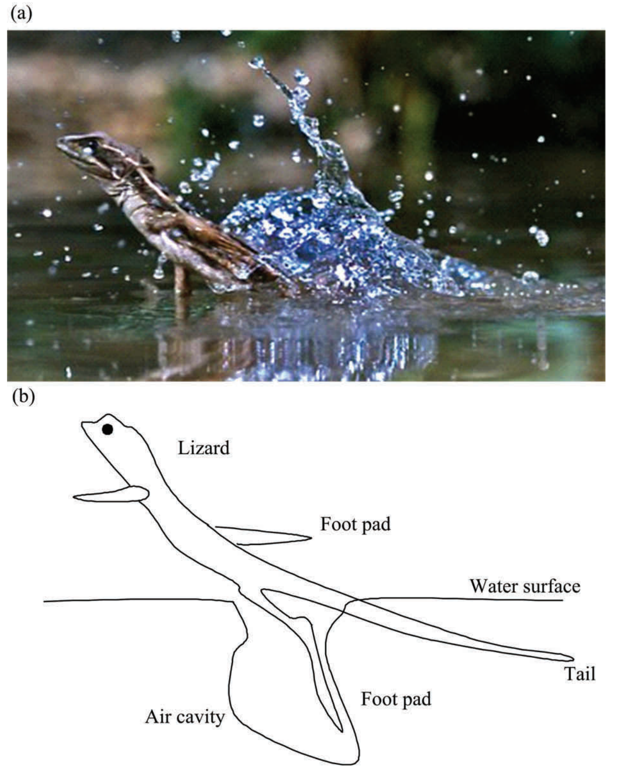

Fig. 1 Posture of basilisk lizard during water running. (a) Image from the BBC's "Earth News"[23] showing the posture during locomotion; (b) simplified schematic to show the posture of the lizard.

in the rolling and yawing directions. We investigated the movement of the lizard and the tail's function as a balancing mechanism. As shown in Fig. 1b, the lizard puts its tail underwater while it runs on the water surface. Intuitively, the tail can balance the rolling and yawing fluctuation. We empirically investigated the performance and sensitivity of the shape and compliance.

2.2 Force analysis of footpads and tail

The process of running on water of a basilisk lizard is divided into slap and drag steps. These steps are applied when the foot is in the water to generate the drag force. The drag force generated by the foot is shown in Fig. 2. Due to this drag force, the basilisk lizard can stay above the water and run forward. The drag force F_D is defined as

$$F_D(t)=C_D S(t)\rho\left(0.5u(t)^2+gh(t)\right), \qquad (1)$$

where C_D is the coefficient of the water resistance, $S(t)$ is the foot area when the foot enters the water, ρ is the density of the water (1000 kg·m^{-3}), $u(t)$ is the instantaneous velocity, g is the acceleration of gravity, and $h(t)$ is