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Analysis and Experiment on the Steering Control of a Water-running Robot Using Hydrodynamic Forces

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Abstract

Steering is important for the high maneuverability of mobile robots. Many studies have been performed to improve the maneuverability using a tail. The aim of this research was to verify the performance of a water-running robot steering on water using a tail. Kinematic analysis was performed for the leg mechanism and the interaction forces between the water and the feet to calculate the propulsive drag force of the water. This paper suggests a simplified planar two-link rigid body model to determine the dynamic performance of the robotic platform with respect to the effect of the tail's motion. Simulations based on a dynamic model were performed by applying a range of motions to the tail. In addition, a simulation with a Bang-bang controller was also performed to control the main frame's yawing locomotion. Finally, an experiment was conducted with the controller, and the simulation and experimental results were compared. These results can be used as a guideline to develop a steerable water-running robot.

Keywords: basilisk lizard, water-running robot, steering, Static Tail (ST), Dynamic Tail (DT), planar two-link rigid body

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1 Introduction

Tails play important roles in the maneuverability of living things. Maneuverability is associated with free movement, such as steering, which can be facilitated by the locomotion of the tail. A tail can generate additional forces to control the orientation of a robot and sometimes generate propulsive forces. Many researchers have examined the functions of the tail. For example, a tail can counteract the torque generated by the body mass when living things climb a wall[1]. The tail reduces the probability of falling. The caudal fin on a marine organism's tail plays an important role in maintaining stability[2]. When external water forces, such as those from waves and sudden streams, make the marine organism unstable, the movement of the caudal fin can maintain the stability of the organism by balancing these forces. In addition, periodical motion of the caudal fin generates hydrodynamic forces for propulsion[3]. Land creatures, such as cheetahs and lizards, also have tails with similar functions[4–6]. Among these creatures, this study focused on a water-running robot inspired by basilisk lizard.

The basilisk lizard is well known for running on water. Glasheen and McMahon[7,8] analyzed the lizard's ability to run on water. Periodical locomotion of the lizard's legs can be divided into slap, stroke, and recovery phases. The legs generate a drag force in the water using the area and velocity of the feet. The generated drag force is divided into lifting force (in the vertical direction) and propulsive force (in the horizontal direction). The lifting force supports the mass of the lizard, and the lizard can run forward using the propulsive force. The Nanorobotics Laboratory at Carnegie Mellon University developed a prototype that mimicked the locomotion of the basilisk lizard for the first time[9]. They also analyzed the roll and pitch motion of the lizard when it runs on water and verified the performance of different types of feet experimentally[10,11]. Related studies have also been conducted in Refs. [12–14].

A tail can provide steering motion for the robot and increase the maneuverability when the robot runs[15]. In the case of the basilisk lizard, it is difficult to steer freely when the lizard runs on water because the tail of the

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lizard is not shaped appropriately to generate a sufficient force. Steering has not actually been observed when a lizard runs on water. This limitation is also caused by the restricted weight with respect to the lifting forces. If this limitation can be overcome, the lizard can steer while running on water and have high maneuverability. Using a tail as a steering method for robots will allow a decrease in the number of actuators compared to velocity differences and expand the robot's range of use. For these reasons, Static Tail (ST) and Dynamic Tail (DT) were used in a robot to realize steering motion. In related research, the Biomimetic Millisystems Lab at UC Berkeley designed a six-legged robot that can steer using the aerodynamic and dynamic forces of a tail[16,17].

In previous research, a six-legged robot that can run on water using the periodic locomotion of the legs was developed. The robot had Styrofoam feet to generate the buoyancy forces[18,19]. Therefore, unlike the basilisk lizard, the robot could float on water without any leg locomotion. The performance for the roll and pitch motion was confirmed, and the results revealed the high stability of the roll and pitch motions for running on water. If the yaw motion can be controlled by the DT, the robot could also run on water while steering freely. Therefore, with the DT, yawing locomotion of the robot was controlled using a Bang-bang controller.

The purpose of this research is to confirm the performance of the steering locomotion using the ST and DT with the Bang-bang controller. A tail with a circular plate attached to the end was used to realize steering locomotion. The propulsive force was determined by kinematic analysis of the leg mechanism. In this study, a simplified planar rigid-body model and a three-dimensional model of the robot was examined. Differential equations to calculate the position and yawing angle of the robot with respect to the movement of the tail were then defined. With the differential equations, dynamic analysis and simulations were conducted to confirm the performance of the steering locomotion. The simulation and experimental results were then compared.

The rest of this paper is organized as follows. Section **2** introduces the characteristics of the robot. Section **3** defines the interaction force between the water and the feet and presents a kinematic analysis of the leg mechanism. In section **4**, a dynamic model for the entire robot is defined, and dynamic equations are then derived to calculate the dynamic locomotion of the robot. Section **5** defines the process of the simulation and shows the results of the simulation. Section **6** suggests the experimental process. Finally, the conclusion is given in section **7**.

2 Three-dimensional modeling of the robot

Fig. 1 presents the three-dimensional model of the robot. The robot consists of a main frame, six legs (Klann mechanisms), and a tail. The robot is driven by a Direct Current (DC) motor, and driving shafts are connected to the DC motor by bevel gears. Three driven shafts are connected to pulleys and timing belts (red line in Fig. 1). The timing belts allow precise rotation of the driven shaft to synchronize the movement of the feet. The robot can run using only one actuator. When the feet move in the water, the submerged area and velocity of the feet generate a drag force. The robot is propelled by the drag forces with respect to the movement of the feet. To generate continuous propulsion, the robot uses a tripod gait. Two tripods are formed by grouping three feet, as shown in Fig. 2. These two tripods have a phase difference of π radians. This means that two legs attached to one driving shaft have the same phase difference as the tripods. Table 1 lists the specifications of the robot.

A tail connected to a brushed servomotor is used to add steering motion to the robot. The servomotor is controlled by the Bang-bang controller. A circular plate is attached to the end of the tail. When the circular plate submerges in the water and the tail rotates, a drag force is generated due to the area and velocity of the circular plate. The drag forces of the tail are transmitted to the main frame of the robot, which affect the robot's

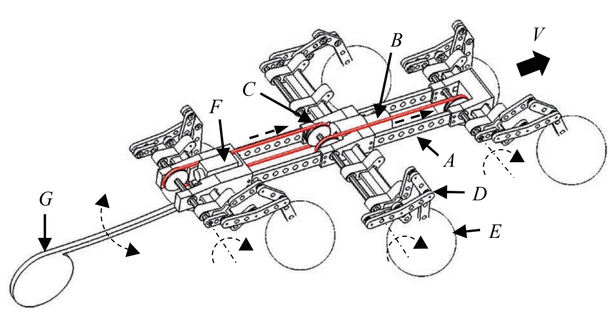

Fig. 1 Configuration of the robot. *A*: main frame; *B*: DC motor; *C*: pulley and timing belt; *D*: Klann mechanism; *E*: spherical Styrofoam foot; *F*: Brushed servo motor connected with the tail; G: tail with a circular plate; *V*: the arrow indicates the moving direction of the robot. The dotted arrows denote the direction of the forces.