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Towards a biologically inspired small-scale water jumping robot

Bongsu Shin, Ho-Young Kim and Kyu-Jin Cho

Abstract— **This paper describes the locomotion of a water jumping robot which emulates the ability of the water strider and the fishing spider to jump on the water surface. While previous studies of the robots mimicking aquatic arthropods were focused on recreating their horizontal skating motions, here we aim to achieve a vertical jumping motion. The robot jumps by pushing the water surface with rapidly released legs which were initially bent. The motion is triggered with a latch driven by the shape memory alloy actuator. The robot is capable of jumping to the maximum height of 26 mm. Jumping efficiency, defined as the ratio of the maximum jumping height on water to that on rigid ground, of a currently developed model is 0.26. This work represents a first step toward robots that can locomote on water with superior versatility including skating and jumping.**

I. INTRODUCTION

Nature has inspired scientists and engineers to understand and recreate its fascinating abilities for a long time. Humanoid robot is one of the typical examples of a design that the engineers have adopted to recreate many mobile abilities of human. Recently, the robotic technology has rapidly expanded its realm mainly by being inspired by biology. Studies of geckos[1] have inspired engineers to build a wall climbing robot[2]; insects with flapping wings[3] have led to the development of a micro-robotic fly.[4] Recent studies of insects that walk on water[5]-[6] have inspired a water strider robot[7] that floats and rows with its long and thin legs. Studies of basilisk lizard[8] that can run on the water has helped the engineers to build a robot that can run on the surface of water[9].

This paper presents a step towards another realm of the interesting abilities that the nature possesses, namely, jumping on water. Aquatic arthropods such as fishing spiders and water striders can jump on water to catch prey or to evade from enemies. Studies of insects jumping on ground have been extensively performed, including the anatomy of the jumping insects.[10]-[12] For an insect to jump, the muscle itself cannot provide enough force and therefore needs to store energy and release the stored energy. This release of the stored energy provides the propulsive force. Jumping on water is a lot more challenging because of the fact that the driving legs are not supported by rigid surface. Instead of the reaction forces of the rigid surface, the legs experience surface tension, drag force, hydrostatic force, and added inertia.[6] For an insect to jump on water, hitting water surface with too much force and speed will result in the penetration of the legs into water instead of lifting the body.[13] Therefore, the legs need move with a speed and force that is large enough to propel the body upwards, but small enough so that the legs will not sink. In this paper, this phenomenon is characterized by experimenting with legs that has different initial bending energy.

There are various hopping robots[14]-[15], including single legged hopping robots[16] and small robot inspired by insects.[17] But the mechanisms that are used in these robots are heavy and bulky compared to the size of robots that can stay afloat on water with surface tension forces. Here a novel small-scale latch mechanism is developed that is incorporated with the robot body and legs. Shape memory alloy (SMA) is chosen for its lightweight and compactness, and the bending of a compliant leg is used to store energy for jumping. The overall weight of the robot is 0.51 g and can jump up to a height of 53.1 mm on the ground, and 11.6 mm on the water.

II. DESIGN CONSIDERATIONS FOR JUMPING ON WATER

The goal of our work is not only to build a robot that can jump on water but also to understand the hydrodynamics and mechanism of the jumping on water. Experiments done with the robot can help better understand the mechanism of jumping on water. Although a lot of studies have been done on the hydrodynamics of walking on water and running on water, jumping on water is a topic that is less understood. The basic design principle of the robot is similar to a water strider robot that rows[18], with a challenge of building a jumping mechanism that is light enough but generates enough drive force to jump vertically. The detailed physics of water walking are dependent on several dimensionless parameters - the Baudoin number $Ba = Mg/\sigma P$, a ratio of the body weight to the surface tension; the Reynolds number $Re = \rho U w/\mu$, a ratio of the inertia to the viscosity; the Bond number $Bo = \rho g w^2/\sigma$, a ratio of the buoyancy to the surface tension; and the Weber number $We = \rho U^2 w/\sigma$, a ratio of the inertia to the surface tension. Here M is the creature's mass, g the gravitational acceleration, σ the surface tension coefficient, P the perimeter where the creatures in contact with water, ρ the water density, μ the water viscosity, U the characteristic velocity, and w is the characteristic length associated with fluid flow.[6] Water jumping arthropods such as water striders and fishing spiders commonly stay afloat effortlessly owing to surface tension because $Ba < 1$.

B. Shin and H.-Y. Kim are with the School of Mechanical and Aerospace Engineering, Seoul National University phone: +82-2-880-9287; e-mail: (sbs2000, hyk)@snu.ac.kr
K.-J. Cho is with the Microrobotics Laboratory, School of Engineering and Applied Sciences, Harvard University. e-mail: kyujin@seas.harvard. edu

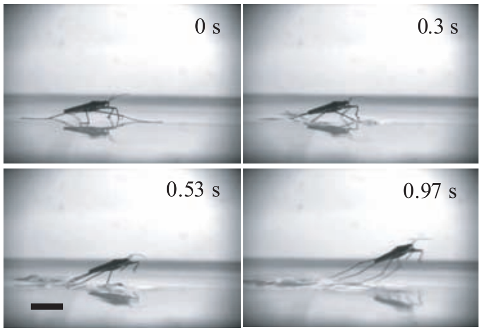

Fig. 1. Images of a water strider jumping on water taken by a high-speed camera. Scale bar, 10 mm.

However, their jumping dynamics may be different from each other as described in the following.

A. Water strider

Careful observation of the water strider jumping on water as shown in Fig. 1 leads us to find that the jumping on water can be divided into two discrete processes. First, the water strider lowers its body by bending its legs, while the driving middle legs starts moving backwards. Second, it uses the middle legs to push the water smoothly to jump. Although this process is similar to that adopted by many insects that jump on ground, the middle legs of the water strider that lower the body do not extend as it jumps. While the front legs hardly move, the hind legs extend once it starts jumping as if it tries to reduce the drag of the legs and to stabilize the direction of jump. It should be noted that there is no splash when the water strider jumps. This implies that the surface tension dominates over the inertia and thus $We < 1$.

B. Fishing spider

The leaping mechanism of the fishing spider has been studied by Suter et al.[20]-[22] When a predatory fish tries to attack the fishing spider floating on the water surface, the spider can evade the attack by jumping vertically from the water surface [20]. Considerable degree of splash is observed when the fishing spider jumps on the water surface, which distinguishes the mode of a fishing spider jumping from the mode of a water strider jumping. A splash, accompanying the formation of an air cavity and rising water rims, occurs when the inertial force dominates the surface tension force, i.e. $We > 1$. Since fishing spiders are normally heavier than water striders, it is necessary for the spiders to generate more force while pushing the water surface for jumping. The only arthropod for which $We > 1$ is the fishing spider in its high-speed galloping mode.[21] Considering the current weight of the robot under development, it was determined suitable to mimic fishing spiders that generate enough lifting force.

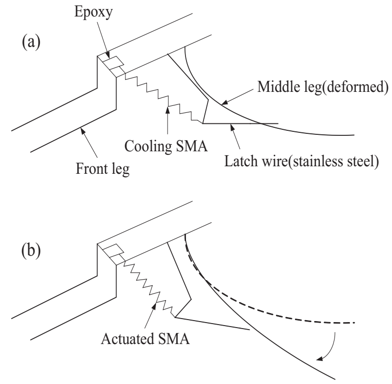

Fig. 2. Schematics of a latch mechanism for the water jumping robot. A compliant leg is used as a spring to store the energy, and SMA is used to activate the latch for releasing the compliant leg from its deformed shape. (a) Before release; (b) After release.

III. DESIGN AND FABRICATION

A. Goal

As stated earlier, the main challenge in designing a robot that can jump on water is to build a jumping mechanism that is sufficiently light. Three components of the jumping mechanism are a spring that stores energy, a latch mechanism that triggers the release of the energy and an actuator that activates the latch mechanism. Average weight of an adult fishing spider is less than a gram.[22] Therefore, our goal is to build a robot with a jumping mechanism that is less than one gram.

B. Latch mechanism

Coil springs are normally used to store energy for jumping in ground-hopping robots. However, we use bending of the compliant legs to store energy before jumping. Fig. 2 shows the schematics of the latch mechanism in the robot. A latch made of a thin stainless steel wire keeps the leg being deformed. An SMA spring actuator is connected to the latch from the body of the robot. When the actuator is activated, the latch moves and releases the leg, generating a large instant jumping force. This is similar to a catapult, whose mechanism is also responsible for the ground jumping of some insects.[12]

C. Body and legs

The water jumping robot consists of a body frame made of an aluminum sheet, 6 legs made of a stainless steel wire and 2 latch wires that support middle legs' initial deformation. The dimensions of the robots are listed in Table 1 and Fig. 3 shows a picture of a fabricated water jumping robot. The legs are attached to the body using epoxy. The front legs and rear legs support the body weight while the middle legs are used for propulsion. These legs are spray-coated with a mixture of chloroform and AKD (alkyl ketene dimer) to turn superhydrophobic. The coating increases the contact angle between the leg and the water to 150°. Robots with less hydrophobic legs having the contact angle of about 110° failed to jump as the legs sank upon hitting the water surface.

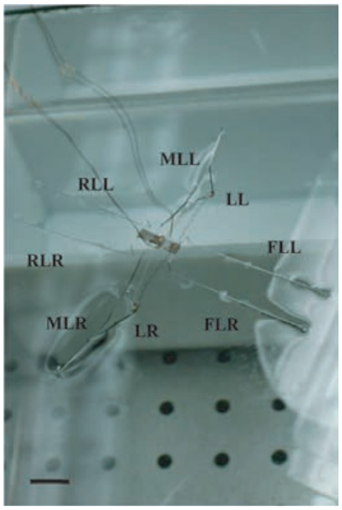

Fig. 3. Fabricated water jumping robot with six legs. LL is the left latch and LR is the right latch. RLR and RLL are the rear legs, MLL and MLR are the middle legs, and FLL and FLR are the front legs. Scale bar, 10 mm.

The middle legs have a larger diameter than the front and rear legs to store energy for jumping. The latch mechanism described in the previous section is integrated in the middle leg. The diameter of the SMA spring actuators is 0.15 mm.

IV. EXPERIMENTS AND RESULTS

SMA spring actuators that release the latch is driven by MOSFETs and the gate voltages for the MOSFETs are generated with an A/D (analog/digital) board that is controlled with LABVIEW software. All electronics are not on-board and the robot is tethered. SMA actuators are driven with a current of 0.4 A with a voltage of 5 V. The middle legs are deformed and latched before being placed on the water surface. As the actuators get active, sequence of images are captured with a high-speed video camera at a rate of 5000 images per second. Using an image conversion software (MotionPro X), the center of mass of the body is measured every 1 ms for the duration of the jump and the data are used to obtain the displacement and velocity of the robot over time. Fig. 4 shows the images of the robot jumping on the water surface, exhibiting considerable amount of splash, which is also typical in a fishing spider's jump. Fig. 5 shows a close-up view of the latch being released and the middle leg pushing the water.

The forces acting on the leg while hitting the water surface include the form drag ($\sim \rho U^2 A$), buoyancy ($\sim \rho g h A$), viscous force ($\sim \mu U L$), added inertia ($\sim \rho V \dot{U}$), and surface tension ($\sim \sigma A/w$), where L is the length of the leg. It immediately follows that increasing the leg area leads to the increase of the reaction force of the water. Thus we attach polyimide sheets of the width of 3 mm and the length 25 mm to the middle legs after coating them with the chloroform-AKD mixture for super water repellency.

A. Maximum jumping height

Fig. 6 shows the vertical trajectory of the robot over time as it jumps on the water. The maximum jumping height

Fig. 5. Close-up view of the driving leg being released from the latch and pushing the water surface. Scale bar, 5 mm.

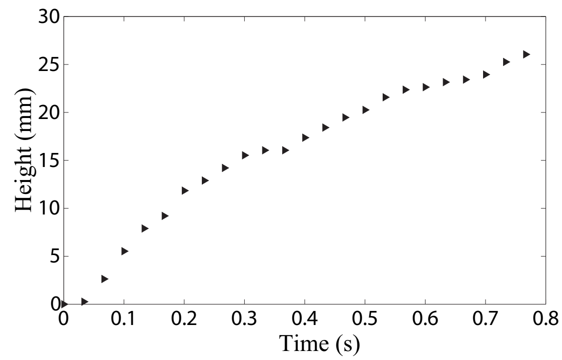

Fig. 6. Vertical trajectory of the robot body over time.

of approximately 26 mm is achieved. Although the robot's actual center of mass is elevated in a monotonic manner, the plot exhibits small fluctuations around 0.4 s and 0.6 s. This is because the marker used to trace the robot location is on the left side of the body, which vibrates slightly during the jump. Fig. 7 shows the instant velocity of the robot obtained by taking the derivative of the height with respect to time.

The vertical forces can be calculated using the two independent methods. Since the initial acceleration is measured to be 1.8 ms^{-2} and the robot weighs 0.51 g, the initial force is calculated to be 0.92 mN. On the other hand, based on the initial velocity of 90 mms^{-1} and the duration that the legs are in touch with water being 33.3 ms, the average force is calculated to be 1.35 mN. We find that the two independently obtained forces are fairly close. As seen in Table 2, the dimensionless numbers of $Re = 260$, $Bo = 0.0054$ and $We = 4.7$ suggest that the physics of jumping of our robot

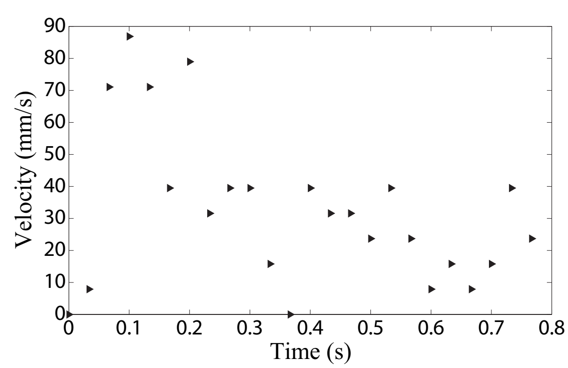

Fig. 7. Velocity profile of the robot over time.

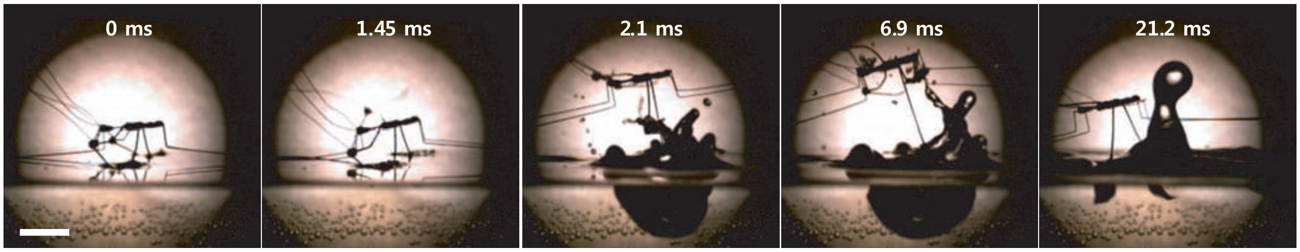

Fig. 4. High-speed video sequence of the leaping of the water jumping robot. Scale bar, 10 mm.

TABLE I
PHYSICAL PARAMETERS OF WATER JUMPING ROBOT

Body width w(mm)	Body length l (mm)	Weight of Robot (g)	Length of FLL, FLR, RLL, and RLR (mm)	Length of MLL and MLR (mm)	Length of LL, LR (mm)	Diameter of FLL, FLR, RLL, and RLR (mm)	Diameter of MLL, MLR, LL, and LR (mm)
3	15	0.51	5	5.5	4.5	0.2	0.4

TABLE II
DIMENSIONLESS GROUPS CHARACTERIZING THE GEOMETRY AND DYNAMICS OF THE WATER JUMPING ROBOT AND AQUATIC INSECTS

	Reynolds number $Re = \frac{Uw}{\nu}$	Bond number $Bo = \frac{\rho g w^2}{\sigma}$	Weber number $We = \frac{\rho U^2 w}{\sigma}$	Baudoin number $Ba = \frac{Mg}{\sigma P}$	Leg aspect ratio $= \frac{w}{L}$
Water jumping robot	260	0.0054	4.7	0.2	0.04
Water strider	$10 \sim 100$	$0.0001 \sim 0.001$	$0.1 \sim 1$	0.03	0.02
Fishing spider	$100 \sim 1000$	$0.01 \sim 0.1$	$1 \sim 10$	0.092	0.12

are similar to those of the fishing spider[3].

B. Water jumping efficiency

Now we compare the maximum height that the robot reaches when it jumps on the ground with the maximum jumping height on the water to deduce the efficiency of the robot in water jumping. On the solid ground, the elastic energy stored in the legs is transformed to the robot's kinetic energy (thus to the gravitational potential energy) and the rest of it is dissipated as heat and sound through ground. On water, however, as the leg hits the liquid surface, the stored energy is consumed to generate the kinetic, gravitational potential, and interfacial energy of water associated with the crater formation. Also viscous dissipation in the water contributes to the energy loss. Thus we expect the jumping height on water h_w to be lower than the jumping height on the ground h_g. The water jumping efficiency η_J, defined as $\eta_J = h_w/h_g$, indicates how efficiently the stored energy is converted to the robot's kinetic energy while reducing the loss imparted to water.

Given the dimensions of the robot, the most important parameter that affects the jumping condition is the hitting speed of the middle legs, U, which in turn is determined by the initial bending degree of the legs. As seen in Fig. 8 the bending angle of the leg is defined as the angle between the leg and the latch. This angle is changed by deforming the leg plastically to different angles. Fig. 9 shows the experimental measurements of the water jumping efficiency versus varying initial bending angles. The efficiency reaches its maximum at approximately 0.26 for the angles ranging between 35° and 47°. The experimental results of Figs. 6 and 7 were obtained by using a bending angle of 47°. When the bending angle or the hitting speed is low, the loss to water is shown to be severe. For high bending angles exceeding 45°, the legs begin to penetrate the water surface, naturally leading to the reduction of the supporting force from water.

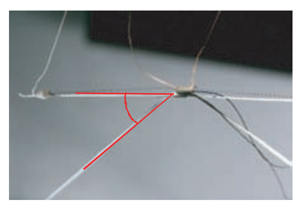

Fig. 8. Angle between the middle leg and the latch wire.

V. DISCUSSION AND CONCLUSIONS

This paper presents initial results of our effort to develop a robot that can jump on water, which is to the authors' knowledge the first report of its kind. The weight of the robot is 0.51 g, which meets our requirement of the weight being lower than 1 g. The magnitudes of the Weber and Bond

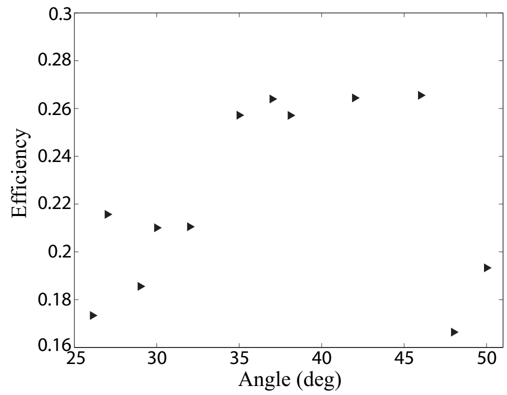

Fig. 9. Water jumping efficiency versus bending angle.

numbers for the robot locomotion are measured to be $We > 1$ and $Bo < 1$, which indicates that its jumping dynamics are similar to those of the fishing spider. The maximum jumping height is 26 mm, 26% of the height reached when jumping on ground.

The current version of the robot is tethered because the electrical setup to power the SMA actuator is located outside. Thus the wires connected to the robot body hamper the jumping motion, reducing the maximum height that the robot can achieve. Therefore, it is necessary to incorporate the electronics with the robot body to remove the tethers. In addition, the robot can jump only once with the current latch mechanism. This guides us to develop a latch system that can hook the legs in an autonomous and repeatable manner. More sophisticated models will be able to find applications in aquatic environment controls and small-scale devices for military operations. Although the currently presented robot recreates the jumping motion of aquatic arthropods using a simplified mechanism, its application can also be extended to the better understanding of the jumping mechanism of various aquatic arthropods.

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