Impact and Surface Tension in Water: a Study of Landing Bodies

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Abstract: The majority of current water strider robots are limited by their ability to jump on the water surface. In order to address this problem, innovative mechanical design can be used. A potential solution is the combination of hydrophobic pads and a spring-based launching device. Incorporating this design would increase the maneuverability of water surface robots. This paper discusses the progress in prototyping and modeling the water strider system.

I. Introduction

Water surface tension is a unique property of water that can be capitalized on to facilitate water movements. This is often done so by a multitude of water-locomotion type insects like the water strider and the diving beetle. These insects often will rest on the water's surface without breaking through it which may result in sinking otherwise.

There are opportunities to use properties adapted by these insects in robotics. By using certain materials and certain configurations of those materials, researchers were able to create robots that glide along the water's surface and even jump on the water's surface, using the surface tension to their advantage. Properties such as hydrophobic and superhydrophobic materials were taken into account as well as limitations such as size and weight of the material configuration.

This report surveys the creation of a robot that can land safely on a body of water without breaking the water's surface, and investigates its ability to subsequently jump off the surface of water. The current technology associated with not invading the water surface by utilizing hydrophobic properties of the robot on the surface tension is researched and specific hydrophobic and super-hydrophobic properties are studied below.

The water strider animal is used as a biological representation of a phenomenon where loads can be applied to the water surface without interfering with the cohesive top layer of the water. Current robots are also studied for their structures and reasoning to be applied to a robot that would possibly apply an instantaneous load onto water and remain afloat. The water strider robot and a different robot designed to jump on water are both researched. Furthermore, there is a study that determines how a falling objects lands on water however, this study in not very comprehensive. Our group hopes to further analyze this property of falling onto water without sinking or breaking the surface of the water.

This study shows some of the properties, materials, methods, and applications of the water gliding robots and proposes an opportunity to explore a new robot that will be able to drop from a certain height and land on the water's surface without breaking the surface tension. Finally, this robot should also be able to actuate and move along the surface once it has safely landed.

Initial Testing:

One foot assembly (3 circular pads) were dropped from various heights, in order to find out if landing on water without breaking the surface tension was even possible. Essentially, if one foot cannot support its own fall from a certain height, it will not be able to support the addition of the weight from the body. Before testing the foot assembly, the bottom surface of the circular pads were freshly coated with hydrophobic coating. The foot assembly was dropped from 1 inch height to 4 inches in .25 inch increment. The result of the test was that the foot assembly could be dropped from 3 inches and land on the water surface without breaking the surface tension. From this result, a realistic goal of 2 inch drop was established for the overall mechanism.

Design Ideas:

The main design challenge is to minimize the downward forces on the foot assembly as much as possible. In essence, the foot assembly should experience a fraction more downward force than it experienced in our initial testing. Two systems, passive suspension system and leg sliding mechanism, were implemented in order to minimize the impact force from the fall as much as possible. The passive suspension system is a spring-damper mechanism that aims to increase the time of contact in order to decrease the impact force according to the following equation:

$$\boldsymbol{Force} = \frac{dImpulse}{dt} \qquad (1)$$

As seen in Figure 1, when the mechanism drops, the ball-joint lowers itself without directly applying the initial impact force due to the spring-damper system. The suspension system slowly lowers the body by dampening, and then dissipates the stored energy after the mechanism has stabilized on water by pushing the body upwards.

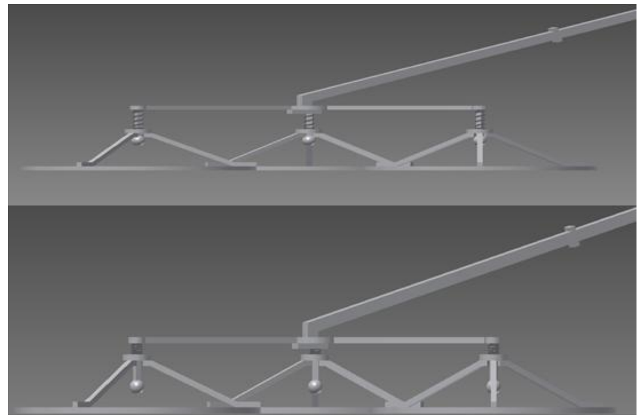


Figure 1. Spring-damper system.

The second system to minimize the downward forces on the foot assembly is the leg sliding mechanism. This system aims to convert the downward force into horizontal force by the leg assembly “contracting.” Instead of the body weight pushing down on the leg-foot assembly, the initial downward force causes the leg-foot assembly to slide inwards as seen in Figure 2a and Figure 2b.

With the combination of spring-dampening system as well as contracting legs, the pad assembly could possibly withstand the impact force. In order to obtain more quantitative results, simulations and calculations were conducted in order to see if the design should be prototyped.

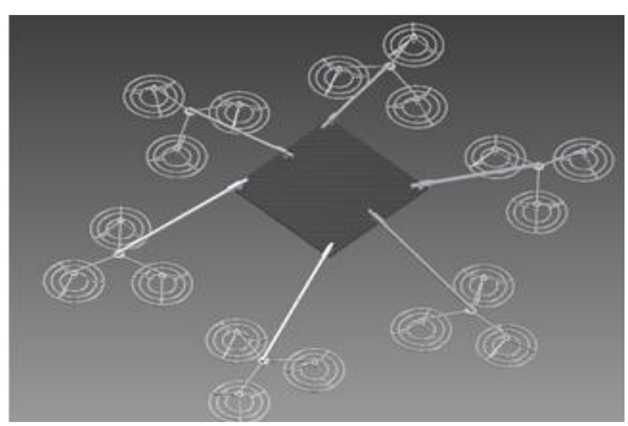


Figure 2a. Before landing

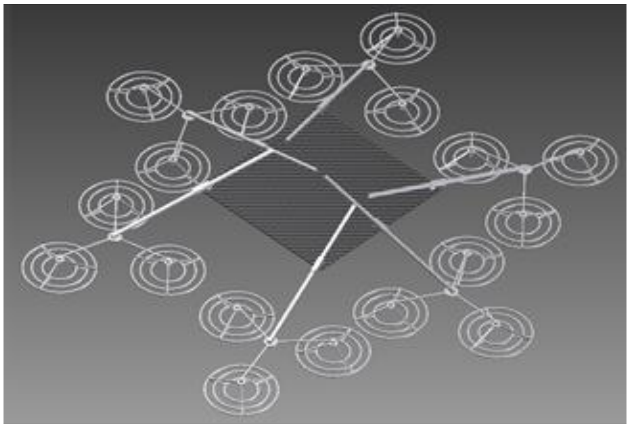


Figure 2b. After landing and contracting

Simulation Setup:

There were two simulations required in order to validate the initial design ideas. The first is to simulate the fall of the entire robot assembly and see if the legs contract. The second simulation deals with finding out the downward force on the foot assembly provided that the first simulation is successful. In order to run these simulations, Autodesk Inventor and Autodesk Simulation Multiphysics were used.

The setup of the first simulation is the robot dropping from the height of 2 inches onto a surface of water under the assumption that the robot will float. In other words, the robot will drop 1 mm below the original water level then rise back up – 1 mm is the thickness of the foot pads, and thus, the robot cannot dip below this point. The friction between the leg and the sliding joint was set to the realistic kinetic friction coefficient between two smooth plastic surfaces (0.2) with lubrication.

Before the simulation, simple free body diagram analysis was done to validate the model. As seen in Figure 3, the following inequality must be satisfied for sliding to occur.

$$mg * Sin(\theta) > F_{friction} \qquad (2)$$

Equation (2) simplifies to the following:

$$Tan(\theta) > \mu \qquad (3)$$

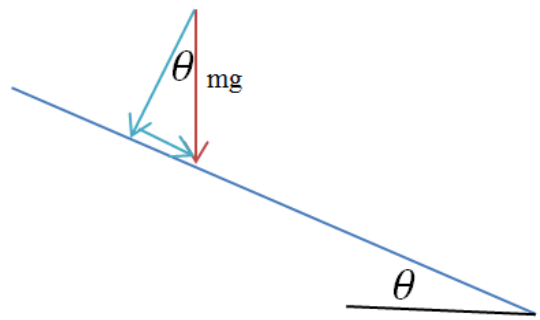


Figure 3. Free body diagram of the leg

For our design, $\theta = 16.7^o$. The inequality condition of (3) is satisfied; thus, the legs should slide inwards. The mathematical model was further validated on Autodesk Inventor's Dynamic Simulation. When dropped from the given height, the legs contracted at the instant the pads touched the water surface.

The next possible problem was the ability of the footpads to actually move on the water surface while contracting without sinking. The combination of hydrodynamic drag and capillary forces could prevent and even submerge the foot pad assembly. It was found by Ozcan et al. [7] that the circular foot pad assembly can travel at the speed of 71.5 mm/s. Through the simulation, the leg was found to travel at 54.2 mm/s which is well below the limit found bye Ozcan et al.

The goal of the suspension system simulation was to perform a parametric study with varying spring constant and damping constant that will allow the foot pad assembly to withstand the impact force.

The impact force of the entire system was calculated through the following.

$$PE = mgh \tag{4a}$$
$$KE = \frac{1}{2}mv^2 \tag{4b}$$

Using Equation 4a and 4b, the velocity right before the impact is:

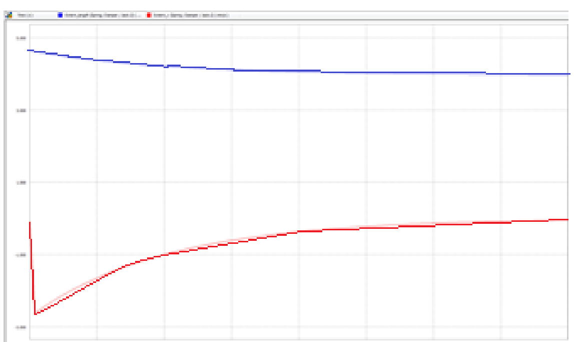
$$v = \sqrt{2gh} \tag{5}$$

Finally, using the work-energy principal:

$$F_{impact} = \frac{KE}{d} \tag{6}$$

The mass of the assembly is approximately m = 50 g, the distance the assembly travels after the impact is d = 1 mm, and the height of drop is h = 2 in = .0508 m. Substituting these values, the following results were found.

$$v = .998\frac{m}{sec} \tag{7}$$
$$F_{impact} = 24.892\ N \tag{8}$$



Since there are six legs, each of the foot assembly experiences 4.1 N of force.

Figure 4. Displacement (blue) and velocity (red) graph

From Ozcan et al. [7], the simulated lift of the foot assembly is 0.375 N for three 20-32-42 mm footpads. Therefore, the combination of the sliding mechanism and the suspension system must decrease the impact force by more than 10 fold.

With the parametric study, the optimal spring constant was found to be k = 2N/mm and the damping constant was found to be B = .5 Ns/mm. As seen in Figure 4, the maximum spring displacement was .67 mm and the maximum spring velocity was -2.226 mm/s.

By using Equation 9, the maximum force on the foot assembly is calculated to be .21 N.

$$F = kx + Bv \tag{9}$$

From this calculation, it was plausible that the contracting leg design and the suspension system can be implemented to have the robot not break the surface tension of the water when dropped from the height of 2 inches. With this validation, prototyping began.

Manufacturing Process:

The entire foot pad assembly was laser cut from a 1 mm Delrin sheet and then sprayed with hydrophobic coating (Smooth-on Universal Mold Release Agent).

The slide joint was made on the 3-D printer which uses ABS plastic. The process of putting the small parts proved to be challenging. Superglue, hot-glue, and epoxy were utilized to assemble the robot.

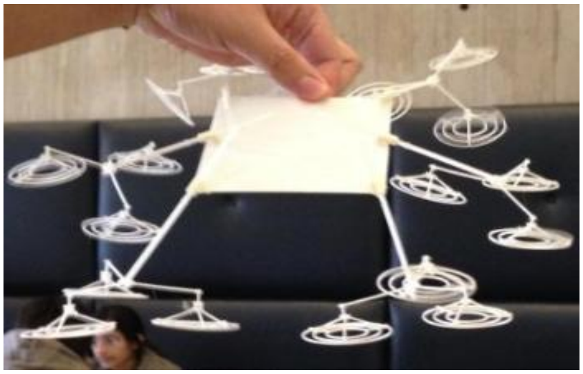


Figure 5. Finished prototype

Prototype Testing and Results:

Unfortunately, the assembly of the prototype had too many mechanical errors. Gluing all the pieces together proved to be extremely difficult and imprecise. This led to increase in the weight of the robot, due to the hot glue and the epoxy, as well as uneven feet. Because the six feet did not align horizontally, they did not hit the water surface simultaneously. Throughout the testing, only 3 or 4 feet landed simultaneously, which barely provided enough lift to hold up the weight of the robot, but not enough to withstand the impact force.

In the next iteration of prototyping, the foot assembly would be entirely 3-D printed to get rid of the need to use adhesives. In addition, the next iteration prototype will use 4 feet instead of 6. With 6 legs, scaling effects dictate that it would be much more difficult for all legs to land at the same time than with 4.

IV. Current Technology: Water Jumper

Design of Current Water Jumper Robot

This study [15] reported a novel micro-robot that could continuously jump on the water surface without sinking, imitating the aquatic locomotive behaviors of a water strider. The robot consisted of three supporting legs while two actuating legs made from super-hydrophobic nickel foam and a driving system that included a miniature direct-current motor and a reduction gear unit. [15] Because of hydrodynamic pressure and the super-hydrophobic nickel foam sheets placed on the ends of the actuating legs, the robot can acquire an instant force while jumping, which allows it to leave the water surface at a speed of $1.6 ms^{-1}$ [15]. This model was used as a base to create the jumping mechanism on the water strider robot created.

The following model, was used in the jumping model for the water strider robot.

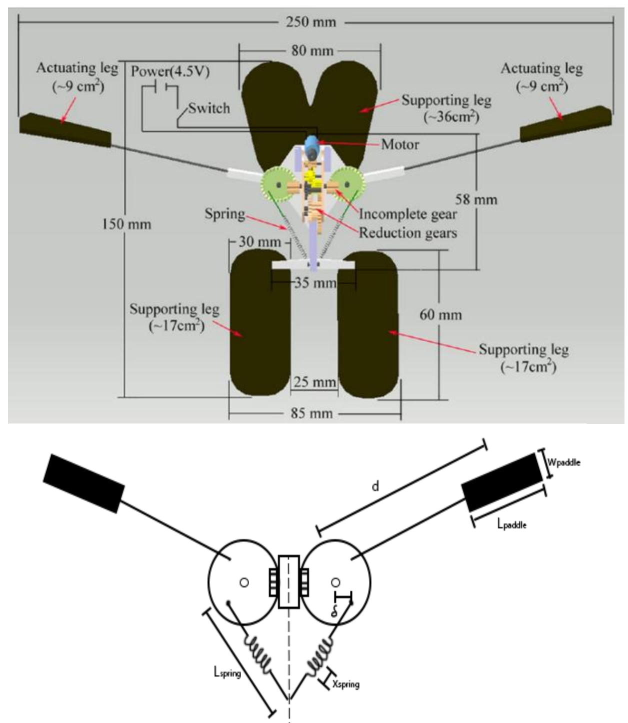


Figure 6 a) Structural robot fabricated. b) Spring model used in jumping mechanism

In order to leave the water surface, the water strider robot has to overcome its own weight and all types of drag force exerted on the supporting legs. Zhao et al. assert that the force required can be expressed in terms of surface tension (F_σ), hydrostatic pressure (F_s), and hydrodynamic pressure (F_d), respectively.

The viscous force is negligible compared to the hydrodynamic pressure, so it is ignored in the mathematical model.

$$F_\sigma = \gamma L \quad (4)$$
$$F_s = -\rho g h S \quad (5)$$
$$F_d = -\frac{1}{2} S \rho v |v| \quad (6)$$

Where γ is surface tension, L is the perimeter, ρ is the density difference between water and air, g is the gravitational constant, h is the height from the supporting leg's bottom to the surface of the water, S is the surface area of the supporting leg, and v is the speed at which the leg falls or leaves the water surface.[15] For the supporting leg, the total force exerted becomes:

$$F = F_\sigma sin\varphi + F_s + F_d \quad (7)$$
$$F = \gamma L sin\varphi - \rho g h S - \frac{1}{2} S \rho v |v| \quad (8)$$

The following figure shows the cross sectional model of the air-water interface as the supporting legs acts.

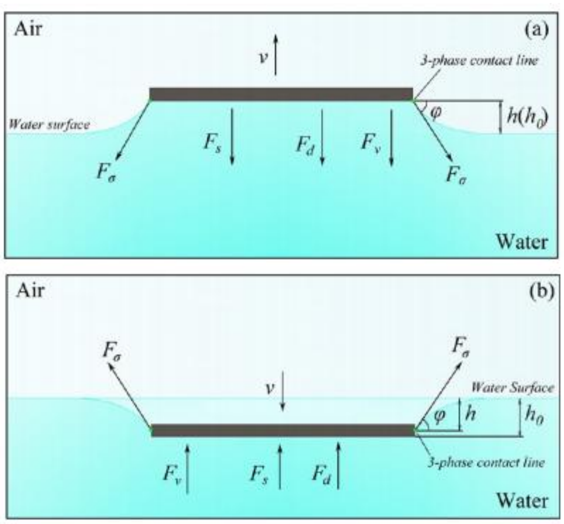


Figure 7. Cross Sectional Model Describing the Air Water Interface of a Supporting Leg (a) Leaving and (b) Falling on the Water Surface.

Zhao et al. states that despite the fact that their micro-robot weighed more than 1100 water striders, it was still able to continuously jump on the water surface with a maximum height of 14 cm.

Using equation 8, listed above, and extrapolating to find the force, the measurement concluded that approximately 1N would be needed to lift the robot 2mm off of the surface of the water. This is sufficient since scaling would increase the necessary applied force and lift the robot even further off of the water surface. This is consistent with Zhao et al. considering their robot was still lighter and had less surface area in contact with the water surface at the time of actuated jumping. Both of these factors would increase the amount of force necessary to lift the robot of the water which was observed in the mathematical model.

Future Work

Two important lessons that our team learned from building the prototype are scaling and manufacturing. Initially, we wanted to increase the size of our payload by increasing the size of the robot, and supporting it with additional circular pads. However, based on the results of our experiments, it seems that the weight of the robot does not scale proportionally to the surface tension and buoyancy. This makes physical sense because there are no large organisms that can support themselves on the surface of the water. We can better address this problem by scaling back the number of legs; although this effectively reduces the payload, the robot will be able to better support itself on the water surface.

In our prototype design, we also underestimated the importance of manufacturing. We concluded that part of the reason the robot was unable to float was because the pads-to-body distances were not identical. The small nuances in the unevenness of the robot resulted in an unbalanced contact with the water surface and additional torques and forces on different points of the robot when impacting the surface. Consequently, the experiment did not match the forces simulated in our model. Since it may be difficult to model the complexity of uneven leg and pad heights while hitting the surface, future work would include a better construction process so that our robot is level and symmetrical.

The legs of a water-jumping micro-robot should move with a force that is sufficiently large to lift the body upward but small enough to avoid sinking themselves, indicating the importance of robot design and the availability of novel materials for legs [15]. In the future, different types of super-hydrophobic material will be experimented with in order to confirm the actuation of the jumping mechanism. A potential implementation of this concept is the nano-groove and pillar structures that are extremely hydrophobic.

In addition to the water strider, we were interested in incorporating an octopus-inspired water propulsion system that would allow us to pull water from the water body and shoot it downwards in order to oppose the falling forces. This idea is currently conceptual only.

Lastly, for Zhao et al. the maximum jumping height increased along with the jumping angle. Notably, the robot jumped lower at β=25° than at β=20°, which indicates that it is possible that the robot has to overcome a larger drag force with higher jumping angle. [15] For future reference, different jumping angles of attack would be experimented with in order determine the best angle for maximum air time. This could increase the distance travelled by robot in each leap.

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