Dynamic Research on a Water Walking Robot Inspired by Water Striders

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Abstract—The superior speed and agility of water strider inspired researchers to design bionic robot walking on water surface. This paper proposed a novel buoyancy based water strider robot driven by decoupled parallel mechanism. Dynamic model of driving mechanism and hydrodynamic model of whole robot were developed in detail. Moving forward and turning experiments were done on prototype under the circumstance of laboratory. For its high efficiency, good mobility, low noise and little disturbance to environment, when equipped with a camera, this robot will have a great advantage in environmental monitoring and military reconnaissance.

Index Terms—water strider, bionic robot, driving mechanism, dynamics, hydrodynamics

I. INTRODUCTION

The living beings in nature are almost perfect through billion years of evolution. They give us inspiration to design biomimic robots working in unstructured circumstances.

Water strider can stand effortlessly and slide or jump quickly on water surface and rarely get wetted. Even on water as shallow as a tenth of an inch it still can walk. People become interested in water strider inspired robot walking on surface. Water strider robot can move fast efficiently and quietly using a sculling motion. So it is simpler and quieter than propeller. Such impressive advantages ensure water strider robot have a wide variety of applications from military equipments to civil devices, e.g. military reconnaissance, environmental monitoring, water quality examination, underground pipe detection, etc.

Various mechanical water striders have been developed in recent years. John Bush from MIT built the first water strider robot which was powered by an elastic thread and very similar to real insect in structure and motion mechanism[1], Metin Sitti from CMU developed STRIDE which used motors and Li-ion battery[2], Japan's Chuo University designed a buoyancy based water strider robot actuated by motors[3], and so on.

Excellent bionic robot design needs not only imitation but also innovation. Very light water strider keeps afloat by surface tension is ok, while for water stride robot it’s not necessarily the same. To fulfill certain job on far-water surface independently, robot needs carry necessary electronics, actuators, power, sensors, and such. So the weight will be a great limitation to practical application[4,5]. With the development of material science, maybe in the future we can build a perfect water strider robot in various aspects, but not now[6,7]. So we developed a buoyancy based robot actuated by micro electromagnets using simple binary logistic control instead of complex servo control of motor. The robot moves and turns by sculling through decoupled parallel driving mechanism. Its simplicity, utility, agility and high load capacity can satisfy the demands of water strider robot.

In this article we will develop the dynamic model of driving mechanism of the robot. Considering water strider robot working on water, we’ll also develop the hydrodynamic model of the driving mechanism and the whole robot. Finally we shall do moving, turning and loading experiments on prototype under the circumstance of laboratory.

II. ROBOT DESIGN

Water strider moves forward by rowing its two middle legs through an elliptic motion trajectory. To get the elliptic motion trajectory a 3 DOF decoupled parallel mechanism is designed as shown in Fig. 1.

![Figure 1 The virtual prototype model of the robot](image)

The robot is actuated by three micro-electromagnets. Electromagnet 1 and 3 are used to achieve forward or backward motion of the driving mechanism, and the electromagnet 2 is for uplifting motion. The end point of rowing leg can get desired elliptic motion trajectory through cooperative control of the two electromagnets. Compare with motor actuated water strider robot, the
robot actuated by electromagnet have been simplified both in structure and in control method[8,9,10].

III. ESTABLISHMENT OF DYNAMIC MODEL OF ROBOT

Dynamic model of driving mechanism is built according to kinetic energy theorem. Based on fluid mechanics theory, hydrodynamic equations are formed for driving mechanism and robot.

Take account of the size of single leg driving mechanism is small, the weight of chosen material is much smaller than electromagnet output force, we suppose the friction of slider and revolute joint is zero in calculation. And so do the moment of inertia and the inertia force.

A. Establishment of dynamic model for driving mechanism

Single leg driving mechanism is simplified as shown in Fig. 2. The sizes of all components in driving mechanism are known, mass and moment of inertia and the position of centroid are also known. Slider 1 and slider 2 are actuators. Driving force \( F_{v1} \) and \( F_{v2} \) are generated by electromagnet 1 and electromagnet 2 respectively. The specifications of the two electromagnets are the same and electromagnet 2 is shared by two legs, so \( F_{v1} = 2F_{v2} \). \( M_x \) is the working resistance torque. Dynamic equation will be built based upon the above assumptions. We want the paddling driving force and acceleration on point C and D under actuation force of \( F_{v1} \) and \( F_{v2} \).

The increment of total kinetic energy of the mechanical system in a transient is equal to the sum of work of all extern force acted on the system at that moment according to the kinetic energy theorem. Take the potential energy as the work of extern force. Here the influence of potential is neglected because of the light material and the low weight of moving iron core of electromagnet 2. So objects are often streamlined to reduce the shape resistance in engineering. The flow resistance includes frictional resistance and lift. The paddle of water strider robot is influenced by flow resistance and lift of water when paddling. The lift is neglected because it is very small. The flow resistance includes frictional resistance and shape resistance. The frictional resistance is shear stress formed by friction between fluid and body surface. The shape resistance, also known as pressure drag, is resistance caused by pressure difference between the back and the front of the body when fluid flow bypass. So objects are often streamlined to reduce the shape resistance in engineering.

The flow resistance on paddle can be calculated by

\[
F_z = C_p \frac{\rho U_0^2}{2} A_p
\]

Where \( F_z \) is the flow resistance on the paddle, \( C_p \) is flow resistance factor, \( U_0 \) is flow velocity which is equal to the rowing leg velocity relative to static water, \( \rho \) is density of fluid and for water it is \( 1.0 \times 10^3 \) kg·m\(^{-3}\), \( A_p \) is the projection area of paddle in the perpendicular direction of flow.

The flow resistance factor \( C_p \) is determined by Reynolds number, shape and surface roughness of the paddle. It is difficult to draw from the theoretical calculation and always determined by experiments. Since the paddle of robot is a thin flat panel and the aspect ratio is 6.25 the \( C_p \) is 1.2.

B. Hydrodynamic equation of driving mechanism

The main resistance of robot when walking on water comes from water resistance of rowing legs and supporting legs. As the water circumstance is very complex we suppose the robot works on calm water surface and only care the water resistance brought by static water in this paper. So we needn’t take into account of waves, flowing of water, and wave forming resistance, etc.

1) Water resistance of paddle

When fluid flows bypass an object, the force on it can be decomposed into flow resistance and lift. The paddle of water strider robot is influenced by flow resistance and lift of water when paddling. The lift is neglected because it is very small. The flow resistance includes frictional resistance and shape resistance. The frictional resistance is shear stress formed by friction between fluid and body surface. The shape resistance, also known as pressure drag, is resistance caused by pressure difference between the back and the front of the body when fluid flow bypass. So objects are often streamlined to reduce the shape resistance in engineering.

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2) Water resistance of rowing leg

The flow resistance on paddle can be regarded as uniform load. As the paddle is perpendicular to the
rowing leg, the paddle can be regarded as a cantilever beam with fixed end at point D.

The water resistance on point D is

\[ F_{dz} = F_z = C_p \rho \frac{U_0^2}{2} A_p \]  \hspace{1cm} (7)

The uniform load of flow resistance on paddle is uniformly distributed along the length direction. It is calculated by

\[ q = F_z / L_p \]  \hspace{1cm} (8)

Where \( L_p \) is the length of paddle.

The distributed load of flow resistance brings about resistance bending moment on point D of rowing leg. It is

\[ M_{dz} = \int q \text{d}x = \int \frac{1}{2} \rho L_p \frac{U_0^2}{2} x^2 \frac{A_p}{L_p} \]  \hspace{1cm} (9)

For the paddle is perpendicular to rowing leg, the moment of \( M_{dz} \) to the rotary center of point A is zero. So the total water resistance moment to the rotary center of point A is

\[ M_z = F_{dz} L_{AD} = C_p \rho U_0^2 \frac{A_p}{L_p} L_{AD} \]  \hspace{1cm} (10)

Where \( L_{AD} \) is the length of rowing leg.

3) Hydrodynamic equation of driving mechanism

Using (10) and (5), we get the hydrodynamic equation of single leg driving mechanism of robot. That is

\[ \frac{d}{dt} \left[ \frac{1}{2} (\rho L_p \frac{U_0^2}{2} \frac{A_p}{L_p}) \right] + J_0 \frac{d}{dt} \left( \frac{1}{2} (\rho L_p \frac{U_0^2}{2} \frac{A_p}{L_p}) \right) + m_0 \frac{d^2}{dt^2} (\rho L_p \frac{U_0^2}{2} \frac{A_p}{L_p}) + m_0 \frac{d^2}{dt^2} (\rho L_p \frac{U_0^2}{2} \frac{A_p}{L_p}) + \rho L_p \frac{U_0^2}{2} \frac{A_p}{L_p} = 0 \]  \hspace{1cm} (11)

Equation (11) is equivalent forms of dynamic model. It describes the dynamic relation of single leg driving mechanism under the driving force of electromagnet and water resistance.

C. Hydrodynamic equation of robot

1) Water resistance of supporting leg

During the moving process the overall water resistance on supporting leg is composed of frictional resistance caused by under-water part of supporting leg and shape resistance. This resistance of supporting leg makes resistance to robot when walking on water. Refer to Eq. (6), we get the overall resistance on supporting leg

\[ R_s = C_s \rho \frac{U_0^2}{2} A_S \]  \hspace{1cm} (12)

Where \( R_s \) is the flow resistance on the supporting leg, \( C_s \) is flow resistance factor, \( U \) is flow velocity, \( \rho \) is density of fluid, \( A_s \) is the projection area of supporting leg in the perpendicular direction of flow.

The flow resistance factor \( C_s \) is related to the shape of supporting leg. Different shape has different \( C_s \). Since the supporting leg of robot is of cylindrical shape and its ratio of Length and Diameter equals to 5 so the \( C_s \) is 0.85.

2) Hydrodynamic equation of robot

During paddling the robot is temporarily considered as a system of particles. The total mass is \( M \). In the vertical direction the gravity and the buoyancy are equal and opposite in direction, So the robot receives a zero force in this direction. We only study the forces in the direction of moving forward.

When robot rows across the water, the water resistance on paddle \( F_z \) propels the robot moving forward, while the water resistance on supporting leg \( R_s \) prevents the robot from moving forward. Other resistance such as wave resistance, resistance produced on paddle when the paddle just thrusting into water or out of water is not taken into account in this paper.

Since the robot has two paddles and four supporting legs, according to Newton second law, we get the dynamic equation of robot

\[ Ma = 2F_z - 4R_s \]  \hspace{1cm} (13)

Where \( a \) is the robot acceleration relative to ground. Using (6), (12) and (13) we get

\[ Ma = C_p \rho U_0^2 A_p - 2C_s \rho U_0^2 A_s \]  \hspace{1cm} (14)

Let \( a = \dot{U} \), \( U_0 = U - v_{dr} \)

Where \( v_{dr} \) is the speed of point D on rowing leg relative to robot.

Then we get the hydrodynamic equation of robot moving on water surface

\[ M \dot{U} = C_p \rho (U - v_{dr})^2 A_p - 2C_s \rho U_0^2 A_s \]  \hspace{1cm} (15)

V. Experiments on Prototype

Based on the dynamic research and other previous job a water strider robot prototype was made. And we did moving, turning and loading experiments on the prototype in homemade tank.

A. Moving forward experiments

Moving speed changes with the size of supporting leg and paddle, driving frequency of electromagnet, load on robot, etc. When the supporting leg radius is 23 mm and length is 100 mm, the paddle length is 50 mm and width is 10 mm, driving frequency is 6.74 Hz, through putting different weight on robot, we get the changing moving speed, described as Fig. 3.
Under above conditions the highest speed of robot is 100 mm·s⁻¹. The robot slows down with the increasing load on it. If the load is under 40 g the speed is above 50 mm·s⁻¹.

B. Turning experiments

Turning experiments are done under the same condition as above except the paddle length is 60 mm. When the two rowing legs of robot are driven differentially, i.e., one rowing forwards and the other rowing backwards, the max angular speed is 12 deg·s⁻¹. The experiment results show the robot make a flexible turn with nearly zero radius when driven differentially. The error is mainly caused by the wire attached to the body of robot which prevents them from turning freely.

The forward speed is related to many factors from above experiments. Under certain range of frequency, robot moves faster with the higher frequency, longer rowing leg, shorter paddle, and lower load.

VI. CONCLUSIONS

According to the research on locomotion mechanism of water strider we put forward a six-leg water strider robot actuated by micro-electromagnet in this paper. Four supporting legs keep the robot from sink by buoyancy. The two rowing legs of robot have elliptic motion trajectory and drive the robot moving forward and turning just the same as its nature counterpart. We build the dynamic model of single leg driving mechanism. Further the hydrodynamic model is developed considering the robot works in water circumstance. Based on the dynamic research of whole robot a prototype is fabricated. Experiments are done on it under the circumstance of laboratory. The results show robot moving speed can reach 100 mm·s⁻¹ and the peak turning angular speed is 12 deg·s⁻¹. Robot will perform better with optimized shape of legs and longer stroke of electromagnet. The developed water strider robot has the advantage of low cost, simple control system, high load capacity, practicability. Equipped with energy, improved control and detection system, the robot can work on far-water surface independently in future.

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