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Design and Simulation of a Robotic Jellyfish Based on Mechanical Structure Drive and Adjustment

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Abstract: This paper presents a novel jellyfish-inspired swimming robot whose mechanical design, control algorithm, and motion analysis are discussed and manifested in detail. In consideration of few research on robotic jellyfish capable of three-dimensional movement with mechanical drive and actuator, we propose an improved design mainly featuring six-bar linkage mechanisms as the actuators and a barycenter adjustment mechanism as an attitude regulator. To imitate the real jellyfish and to reduce drag, the robotic jellyfish is comprised of a streamlined head, a cavity shell, and an elastic rubber skin around the drive units. Meanwhile a bio-inspired central pattern generators control model is imported. To validate the feasibility of the maneuverability with designed motion mechanism and free attitude regulation, dynamic analysis and simulation experiment are conducted. The obtained results show the conceived novel robotic jellyfish can accomplish all motion tasks desired.

Key Words: Robotic jellyfish, Linkage mechanisms, Barycenter adjustment mechanism, Simulation

1 Introduction

With the rapid progress of robot technology and the prosperousness of robotics, more and more kinds of robots have emerged to assist human being in achieving the tasks beyond their abilities. Profiting from the nature's gift and inspiration, bionic technologies applying to robots spontaneously become an ideal choice for robot design and implementation. Underwater bionic robots, as an extraordinarily important branch of biomimetic robots, attract much attention. Many unmanned underwater vehicles (UUVs) have been proposed by worldwide researchers theoretically and experimentally to tackle underwater tasks, most of which are characterized by bionic design and have substantially promoted the research level on bio-inspired swimming and control.

On the basis of locomotion actuating features, fish swimming mode can be classified into three main modes: body and/or caudal fin (BCF) mode, median and/or paired fin (MPF) mode and jet propulsion (JET) mode. Most fish generate thrust by BCF movements and some are using MPF mode. This classification of swimming movement is originally put forth by Breder [1]. Beyond that, JET mode, a kind of acceleration pattern of jellyfish (*Aequorea Victoria, Mitrocoma cellularia and Phialidium gregarium*), has commonly been regarded as a significant thrust-generation mode for fish swimming. Further more, considering that jellyfish can detect the direction of ocean currents and advance by their orientation abilities, flexibility, and energy conservation capability incredibly, more and more bio-mechanisms come to resort to the JET mode as motive power source for the biomimetic robot.

In previous studies based on biomimetic design and analysis, many researchers have attempted to use traditional actuators and multiple motors to fabricate underwater robots mimicking jet propulsion. Additionally, some of them have made some achievements. In spite of good performance, their body sizes are quite large attributed to multiple sets of actuators to achieve their performance and meet certain requirements. As a consequence, in the early studies for jet propulsion applying to underwater robots, smart actuators such as SMA (shape memory alloy), IPMC (ionic polymer metal composite), EMA (electromagnetic actuation), and hybrid ones are adopted prevailingly [2].

Alex Villanueva *et al.* [3] from Virginia Institute of Technology designed and fabricated an underwater vehicle mimicking the propulsion mechanism and physical appearance of a jellyfish. The robotic jellyfish called Robojelly used bio-inspired SMA as actuators. Robojelly was 242 g in weight, 164 mm in bell diameter and consumed approximately 17 W of average power. Joseph Najem and Donald J. Leo [4] from Center of Intelligent Material Systems and Structures in Virginia Tech presented a biomimetic jellyfish robot that used IPMCs as flexible actuators for propulsion. IPMCs are synthetic composite nanomaterials that display artificial muscle behavior under an applied voltage or electric field. The critical components of the robot included the flexible bell, a central hub and a stage used to provide electrical connections and mechanical support to the actuators. Through producing a mechanical deformation of IPMCs under an electric field, a jet propulsion could be accomplished. Youngho Ko *et al.* [5] from Chonnam National University in Korea proposed a jellyfish-like swimming mini-robot actuated by an EMA system in space. The jellyfish-like mini-robot had four flexible fins, each of which was equipped with a permanent magnet for electromagnetic actuation. The robots body was 17 mm long and 0.5 mm thick. The EMA system was able to produce a uniform magnetic field in a desired direction in three-dimensional (3D) space, which could bend the fins of the jellyfish-like robot to generate thrust. Yunchun Yang *et al.* [6] from Harbin Engineering University and Kagawa University presented a new prototype model of an underwater jellyfish-like microrobot using hybrid of SMA and ionic conducting polymer film (ICPF) as the actuators to realize swimming motion. The size of the microrobot was about 75 mm long, 6.5 g in weight, and 55 mm in diameter. However, unlike a real jellyfish, this robot generated thrust through the

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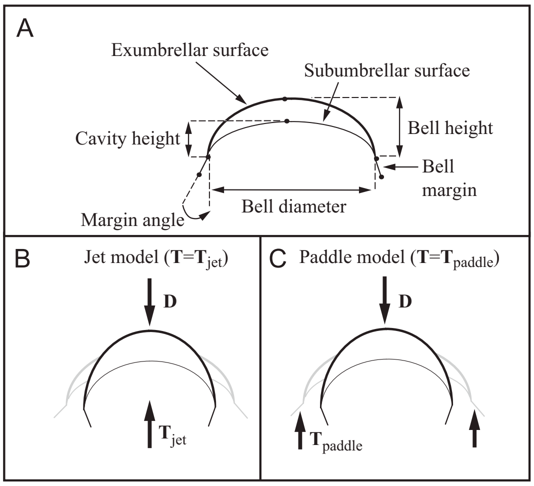

Fig. 1: McHenry's morphometrics and hydrodynamic modeling of jellyfish.

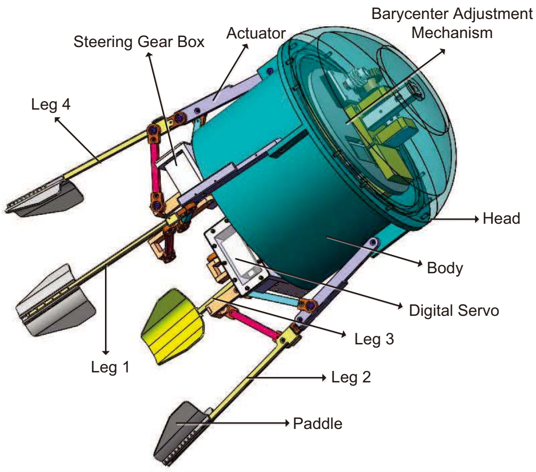

Fig. 2: Mechanical configuration of the robotic jellyfish with paddles.

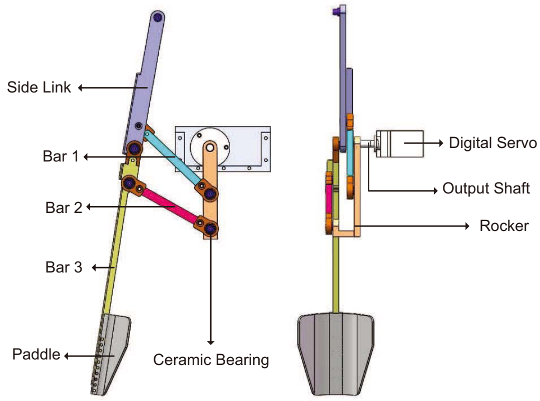

Fig. 3: The actuator part of the mechanical design of the robotic jellyfish.

bending movement of the actuators.

The jellyfish-like robots using smart actuators reported above have similar advantages such as small volumes, reduced size, attenuated weight, noise reduction, and low power consumption. Nevertheless, they have common drawbacks as well. Compared with other robot types and underwater animals, robots using smart actuators are excessively slow in speed ,and in general, slower than robots using motors. Therefore, developing an innovative type of robotic jellyfish based on mechanical structure drive and with free movement ability has become current urgent trends. In this study, we develop an improved free-swimming biomimetic robotic jellyfish based on four six-bar linkage mechanisms as the actuators and a barycenter adjustment mechanism as an attitude regulator after analysis of morphology, kinematics, hydrodynamics, modeling, control and simulation.

2 Mechanical Design

2.1 External Body

In biology, a jellyfish is a form of cnidarian in which the body is shaped like an umbrella. The upper surface is termed as the exumbrella and the lower surface is termed as the subumbrella. Transparent mesoglea constitute most of the bell texture with numerous radially arranged fibres attached around the margin. Circular muscles form the subumbrellar surface and play a leading role for powering the locomotor cycle. The cycle start with the contraction phase, in which jellyfish reduce the diameter of the bell. While shrinking, water contained in the bell cavity is ejected through the orifice, and the jellyfish is propelled in the opposite direction, thus thrust is generated and the jellyfish begin to move [7]. In order to understand how changes in size, shape and behavior affect the hydrodynamics of jet propulsion in the jellyfish to explore how such changes affect the ontogenetic scaling of swimming speed and cost of transport, McHenry *et al.* [8] conducted a series of experiments and simulations. Their work made some great achievements. McHenry's morphometrics and hydrodynamic modeling of jellyfish is illustrated in Fig. 1. Inspired by physical characteristics of motion mechanism of *Aequorea victoria*, we develop a compact robotic jellyfish scheme. For external body, the robotic jellyfish consists of an umbrella rigid head, a cylindrical hollow body for housing the embedded controller, the battery pack as well as barycenter adjustment mechanism, and four actuators based on a six-bar linkage mechanisms as showed in Fig. 2. The determination of the shape for the head and the body is in consideration of drag reduction and morphology imitation of the real jellyfish. The head and the body are assembled together through an O-type sealing ring in consideration of waterproofing. Four drive mechanisms and four actuators are centrally symmetric about the center axis of the cavity. An elastic rubber skin is enwrapped around the actuators. This design inspiration refer to mimicking the tentacle and the subumbrella of the real jellyfish. Therefore, four actuators motion bringing six-bar linkage mechanisms along in water can create a swirling vortex flow which generates the thrust to make the robotic jellyfish move. The actuation unit consists of a digital servo, a rocker, three bars, and a side link. These frameworks mainly are jointed by ceramic bearings and showed in Fig. 3. As a result of the limitation of space, the digital servos are put outside the body and enwrapped by specialized steering gear box. The connection between steering gear box and the body as well as the link between output shaft and the rocker are all applied O-type sealing ring in view of waterproofing. The movement source of the robotic jellyfish stems from the four digital servos.

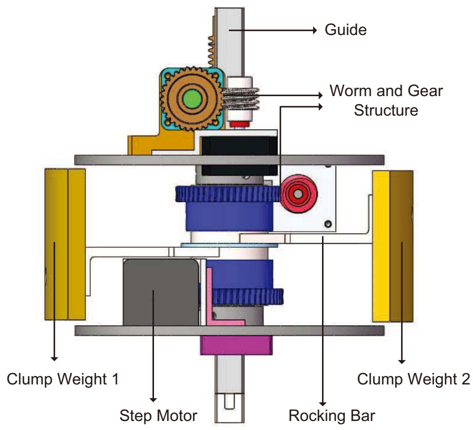

Fig. 4: Barycenter adjustment mechanism in equilibrium state.

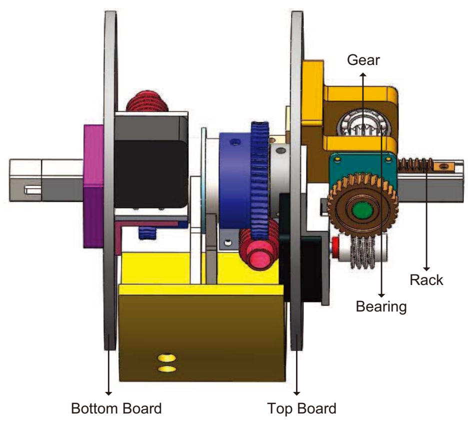

Fig. 5: Barycenter adjustment mechanism in partial inverted state.

The driving shaft of the digital servo rotates to put rocker in motion, thus driving Bar One and Bar Two. Consequently, the side link and the Bar Three with Paddle start to be actuated back and forth periodically.

There remains no connection interface on the outer shell, because the robotic jellyfish will adopt wireless control mode using wireless signal transceiver module RF200 to realize the robotic jellyfish's remote control.

2.2 Internal Organization

Through the design of external form and mechanisms, the robotic jellyfish is able to locomote like a real jellyfish. However, it is not far enough merely capable of moving as a real jellyfish. The locomotive morphological characteristics is of great importance. In terms of underwater attitude, the head orientation of a jellyfish depends on the relationship of the center of gravity and the center of buoyancy. Hence, in order to change the attitude of the robotic jellyfish in water, the center of gravity should be altered timely. Yet unfortunately, in the previous studies, there is not any research that barycenter adjustment mechanism is applied to the robotic jellyfish. In our studies, we designed a unique barycenter adjustment mechanism so as to realize the function of gravity center adjustment for the robotic jellyfish as illustrated in Fig. 4 and Fig. 5. In the barycenter adjustment mechanism, the realization of shift function for barycenter counts

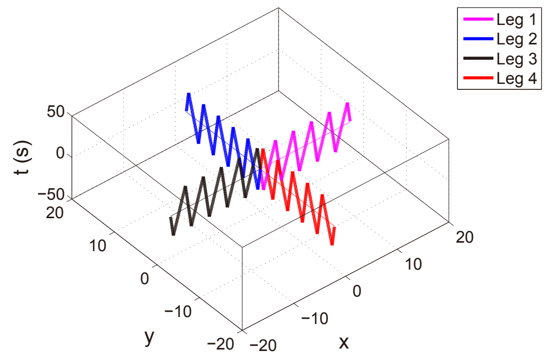

Fig. 6: Control signals of the robotic jellyfish. Note that x-coordinate and y-coordinate represent the relative position of the four actuators.

on two clump weights which are made of red copper and weigh one kilogram each. The clump weight is connected to a step motor by a rocking bar and a gear set. Thus, it can rotate through control of the step motor to achieve performing range scans of a perigon. By the horizontal movement of the clump weight, the center of gravity can be shifted in the horizontal direction. In order to realize the self-lock of the screw thread for protecting the step motor, worm and gear structure is applied to the gear set.

If viewed as a entirety for two clump weights, they can be treated as one whole clump weight to shift in the vertical direction. One step motor is laid on the top board and coordinated through the worm and gear structure with guide and rack structure drawing out from the center of the top board and the bottom board. For the same reason, worm and gear structure is applied to the gear set.

Consequently, the center of gravity can shifted in the horizontal and vertical direction, so that the locus of barycenter is able to enwrap the center of buoyancy. Hence, the attitude of the robotic jellyfish can be adjusted and changed easily and freely. The specific shift degree will be discussed in the following part.

3 Control Algorithm

Central pattern generators (CPGs) are a kind of biological neural networks that produce rhythmic patterned outputs without sensory feedback. CPGs have been shown to produce rhythmic outputs resembling normal rhythmic motor pattern production even in isolation from motor and sensory feedback from limbs and other muscle targets. Due to the advantage of serving many functions in vertebrate animals, CPGs have been widely used by research on robot control since proposed [9, 10]. In that the leg motion of the robotic jellyfish features the cyclical rhythms, CPG control model is imported in this paper. Particularly, we propose a triangular wave signal oscillator [11]. The four actuators actuated by digital servos can be manipulated independently by the angular wave signal. The collaborative control signal is illustrated in Fig. 6. From the figure it can be seen that P-WM signals are adopted. The periodic and time-dependent control signals are generated by the main microcontroller, and produce the undulation of the servos and the actuators. Thereby thrust force is generated via vortex engendered by interaction between the limb-paddle unit and water. Specifically, by means of modulating the oscillating frequency, velocity control of the actuators can be adjusted, while direction control is realized by offset control of the four actuators harmonically.

4 Dynamic Analysis and Simulation

4.1 Motion Process of Link Mechanism

The swimming motion process of jellyfish are divided into two phases: the contraction phase and the relaxation phase. During contraction, cycloidal subumbrellar pull the muscles in an aboral direction to reduce the volume of the subumbrellar cavity and force water out of the bell. During the relaxation phase, water is drawn back into the subumbrellar cavity as the bell returns to its resting shape. Because there are no muscles which oppose the subumbrellar muscles, the relaxation phase results from the release of elastic energy stored in the bell, just as a rubber band snaps back upon release of a load [12].

Similar to the real jellyfish, the motion of the robotic jellyfish is modeled with a momentum balance for an accelerating mechanism. Combining the research findings and results of Daniel and McHenry, the model consists of four main terms and can be written as a differential equation whose solution describes the kinematics of swimming robotic jellyfish. The formula concerning the kinematics and dynamics of the jellyfish can be expressed as follows

$$\mathbf{T} = \mathbf{D} + \mathbf{A} + \mathbf{F} \tag{1}$$

where **T** is the sum of thrust, **D** is the drag, **A** is the acceleration reaction force, and **F** is the force to overcome inertia of animal. The detailed expressions are listed below.

$$\mathbf{T} = \mathbf{T_{jet}} = (\,\rho/A_v\,)\,(\,\Delta V/\Delta t\,)^2\,, \tag{2}$$

$$\mathbf{D} = 0.5C_d\rho S u^2, \tag{3}$$

$$\mathbf{A} = \alpha\rho V(\Delta\mathbf{u}/\Delta t), \tag{4}$$

$$\mathbf{F} = m(\Delta\mathbf{u}/\Delta t), \tag{5}$$

where $\mathbf{T_{jet}}$ is the thrust generated by a jet, ρ is the density of water, A_v is the instantaneous projected bell velar aperture area (A_v=0.25 πd^2, where d is the bell diameter and varies with time), V is the instantaneous cavity volume, t is time, thus $\Delta V/\Delta t$ is the rate of volume change of the animal during either phase. C_d is the drag coefficient, S is the area of the animal projected in its direction of motion. u is the instantaneous velocity of the animal, thus $\Delta\mathbf{u}/\Delta t$ is the accelerated velocity of the animal during either phase. α is the added mass coefficient, a dimensionless term which reflects the effect of shape on the acceleration of fluid around an object, m is the mass of jellyfish.

Thrust acts in a direction opposite to the motion of the ejected water. Hence during the contraction phase, when water is expelled in an oral direction, thrust comes into being in an aboral direction which reverse the flow direction. Conversely, during the relaxation phase, thrust emerges in an oral direction. As a result, switching the processing phase, thrust term may only reverse the sign directly [13]. Note that for a constant rate of volume change, the magnitude of the thrust is inversely proportional to the square of the duration

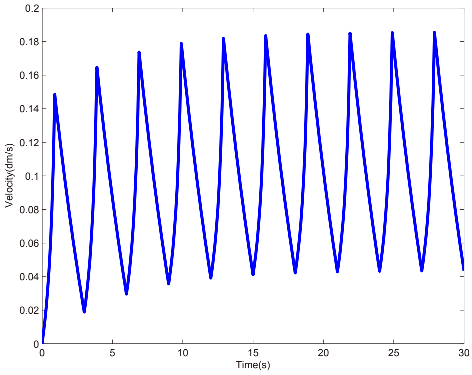

Fig. 7: Instantaneous velocity against time.

of the contraction or relaxation phase. As long as the jellyfish moves with nonzero relative velocity to its fluid environment, drag exists regardless of the phase of the swimming cycle. All factors in Eq. 2 to Eq. 5, except the density of water, vary in time for a swimming jellyfish. Besides the obvious variation in velocity, shape changes of the swimming animal make C_d and S variable in time.

Consequently, Eq. 1 can be expressed as follows:

$$\begin{aligned}(\,\rho/A_v\,)\,(\,\Delta V/\Delta t\,)^2 =\\ 0.5C_d\rho S u^2 + \alpha\rho V(\Delta\mathbf{u}/\Delta t) + m(\Delta\mathbf{u}/\Delta t)\end{aligned} \tag{6}$$

Because the movement mechanism and principle of the robotic jellyfish are basically the same with the real jellyfish, the formula above can also be applied to our novel robotic jellyfish. Further more, the motion mechanism of limbs of the robotic jellyfish is able to be controlled by host computer artificially, hence, time-varying physical quantity in the formula above including ρ, A_v, $\Delta V/\Delta t$, α and m can be calculated, becoming the known quantities. Therefore, the accelerated velocity $\Delta\mathbf{u}/\Delta t$ can be derived by the following formula:

$$\frac{\Delta\mathbf{u}}{\Delta t} = \frac{(\,\rho/A_v\,)\,(\,\Delta V/\Delta t\,)^2 - 0.5C_d\rho S u^2}{\alpha\rho V + m} \tag{7}$$

As a result of that A_v, C_d, V, S, α and m are all time-dependent quantities or functions, the time-varying differential equation above is programmed and simulated in MATLAB (version 8.1; Mathworks). As for our robotic jellyfish, through arithmetic calculation and evaluation, we can obtain the figures of simulation result as Figs. 7 and 8.

From Fig. 7 , conclusion can be educed that velocity of the robotic jellyfish changes periodically and in every cycle the velocity of movement is a two-stage process, one is contraction phase, the other is relaxation phase. Further more, from Fig. 8, we can see that the average velocity is increasing with periods. But we can see that, as time goes on, the average velocity of the robotic jellyfish will be steady in a relatively stable value. Similarly, the acceleration of the swimming robotic jellyfish is not uniform in time and varies periodically, and the movement in acceleration stage and deceleration stage undergoes two different stages as showed in Fig. 9. From Fig. 10 the overall distance in certain cycles can be gained.

The simulation is conducted with digital servos rotating at 0.9°/20 ms in contraction phase and 0.45°/20 ms in relax-

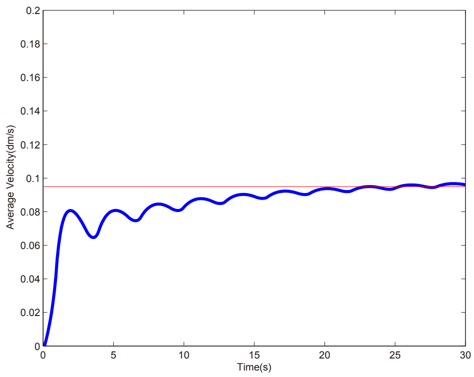

Fig. 8: A plot of the average velocity as a function of time.

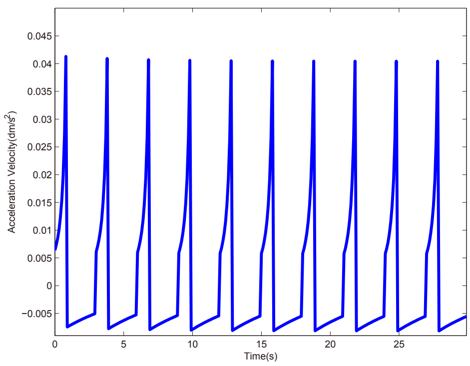

Fig. 9: Instantaneous acceleration against time.

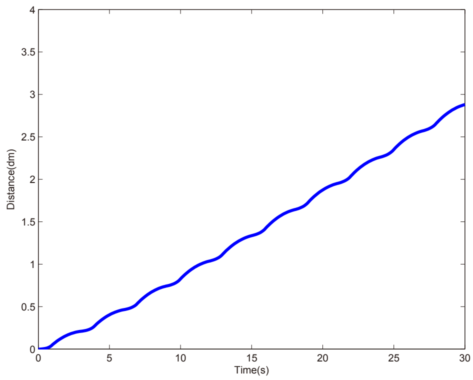

Fig. 10: Distance travelled with cycles.

ation phase averagely, far below the speed limit of 7°/20 ms for digital servos. As long as to change the rotating speed of digital servos, the quantities above can be obtained with ease.

4.2 Motion Process of Barycenter Adjustment Mechanism

Except for the maneuvering with the movements of four legs, turning without radius by virtue of barycenter adjustment mechanism of the robotic jellyfish should be discussed essentially. Motion mechanism of the barycenter adjustment mechanism can be viewed as two main parts. The two clump weights can rotate around the center guide rail arbitrarily so long that their included angle is greater than 60 °. The influence of the barycenter of two clump weights only impact on the horizontal component. So if we set a starting line, the coordinates of barycenter of clump weight one can be

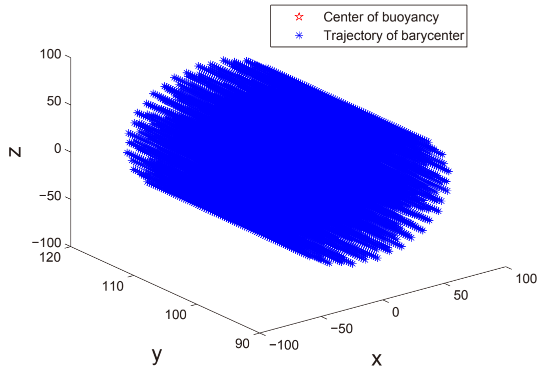

Fig. 11: The relationship between the change of barycenter and the position of the buoyancy center from 3D view.

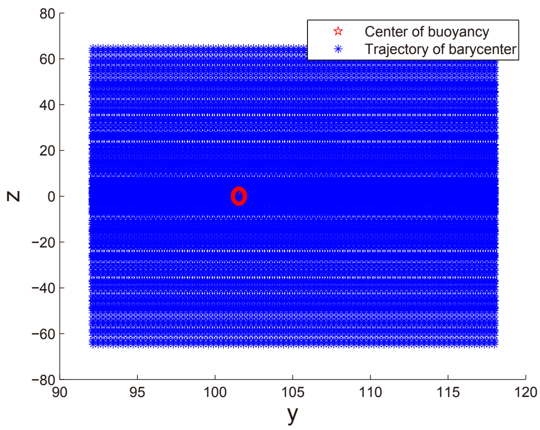

Fig. 12: The relationship between the change of barycenter and the position of the buoyancy center from Y-Z view.

expressed as

$$\mathbf{barycenter}_1 = (l sin\phi, h, l cos\phi)^T \tag{8}$$

Likewise, the coordinates of barycenter of clump weight two is

$$\mathbf{barycenter}_2 = (l sin\psi, h, l cos\psi)^T \tag{9}$$

The coordinates of horizontal component of the barycenter adjustment mechanism is

$$\mathbf{barycenter}_{ho} = \begin{pmatrix} \frac{l(sin\phi + sin\psi)}{2} \\ h \\ \frac{l(cos\phi + cos\psi)}{2} \end{pmatrix} \tag{10}$$

where h is the cross-section coordinates of the section where the clump weights lies. l is the distance between the barycenter of clump weight with rocking handle and the center line of the guide rail. ϕ and ψ are the included angle between starting line and the center line of two rocking handle respectively.

As for the coordinates of the barycenter of whole robotic jellyfish, the only calculation needed to be operated is y-coordinate proportion computing of the barycenter adjustment mechanism and the the external cavity of the robotic jellyfish in vertical direction. If the coordinates of barycenter of external cavity of the robotic jellyfish is expressed as

$$\mathbf{barycenter}_{ve} = (0, f, 0)^T \tag{11}$$

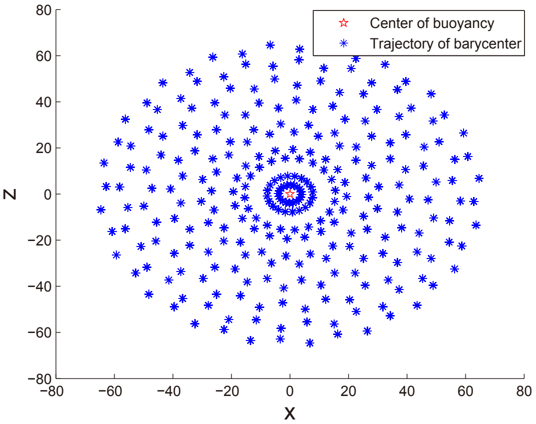

Fig. 13: The relationship between the change of barycenter and the position of the buoyancy center from X-Z view.

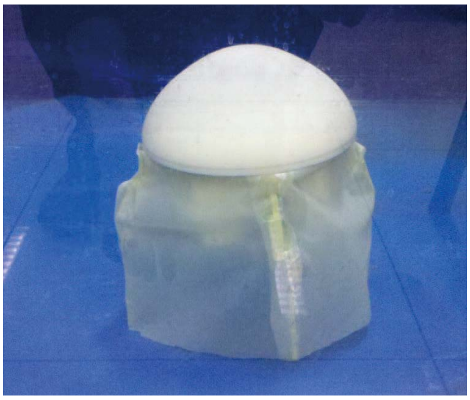

Fig. 14: The prototype of the novel robotic jellyfish.

The coordinates of the barycenter of whole robotic jellyfish is

$$\mathbf{barycenter} = \begin{pmatrix} \dfrac{l(sin\phi + sin\psi)}{2} \\ \dfrac{hm_1 + fm_2}{m_1 + m_2} \\ \dfrac{l(cos\phi + cos\psi)}{2} \end{pmatrix} \tag{12}$$

where m_1 and m_2 are the mass of the barycenter adjustment mechanism and the external cavity of the robotic jellyfish respectively. f is the y-coordinate of the barycenter of the external cavity of the robotic jellyfish.

Through calculating and simulating in SolidWorks(R) Premium 2014, m_1 and m_2 are 5.153 kg and 2.827 kg. By programming and simulating in MATLAB (version 8.1; Mathworks), the relationship between the range of barycenter and the center of buoyancy is showed in Figs. 11–13. From the simulation figures, we can see that the trajectory of the barycenter of the robotic jellyfish completely surrounds the center of buoyancy. The maximum deviation distance of the barycenter away from buoyant center can reach 16 mm in vertical direction and 64 mm in horizonal direction respectively, which sufficiently makes the attitude of the robotic jellyfish transform freely on a spherical track.

At present, the physical prototype of novel robotic jellyfish under construction is illustrated in Fig. 14. The proposed mechanical design and control methods are being verified via extensive experiments.

5 Conclusion and Future Work

In this paper, we have developed a novel self-propelled jellyfish robot based on six-bar linkage mechanisms and the barycenter adjustment mechanism. By mimicking the jet-propelled swimming mechanism of real jellyfish, the robotic jellyfish with four actuators exhibits similar propulsion behaviors. By means of dynamic analysis and simulation, it is verified that the attitude of the robotic jellyfish can be altered arbitrarily. By coordinately controlling the four actuators, the robot can achieve maneuvering with maximum velocity of 18.6 mm/s. With these swimming abilities, the robotic jellyfish may well serve as an effective platform for underwater reconnaissance and environmental monitoring.

In the near future, more effort will be put on improving control algorithms to make it locomote more fast, flexibly, and realistically. Meanwhile, more appropriate material will be adopted to replace the elastic rubber skin to improve the efficiency of movement. Further more, more sensors will be incorporated, thus it will become an information collection point and network node. In the long term, for the purpose of building a mobile aquatic platform, more practical aspects of jellyfish robots should be taken into consideration.

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