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Development of a Novel Robotic Jellyfish Based on Mechanical Structure Drive and Barycenter Adjustment

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Abstract— **Jellyfish-inspired jet propulsion and robotic implementation have drawn much attention among the scientific community. In this paper, we report a novel robotic jellyfish synthesizing mechanical structure drive and barycenter adjustment mechanism. The robotic jellyfish relies on six-bar linkage mechanisms as actuators to realize the contraction-relaxation jet propulsion motion. To imitate the real jellyfish and to reduce drag, the robotic jellyfish is comprised of a streamlined head, a cavity shell, and a latex skin is enwraped around the drive units. To achieve free switch between different motion modes and transform attitude arbitrarily, a barycenter adjustment mechanism is embedded in the robot body. Through the upward, downward, balancing, as well as leaning-down motion of clump weights, the center of gravity of the robot can enwrap its center of buoyancy. Experimental tests on the actual robotic jellyfish verify the great 3D swimming ability.**

I. INTRODUCTION

Unmanned underwater vehicles (UUVs) serve a valuable function in the monitoring of animals, humans and environmental activity. Several applications can be cited for small UUVs including monitoring of ocean currents and chemical agents, study of animal migration, depth measurements and military functions. However, current technologies deployed for many of these applications suffer from practical limitations including cost-effectiveness, strong noise and lifetime. The goal of our research is to develop an unmanned vehicle that is capable of overcoming the drawbacks above, maneuvering and cruising in the water autonomously. As a consequence, we adopted underwater jet propulsion mode inspired by jellyfish to accomplish this goal.

On the basis of actuating characteristics, 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. The classification of swimming movements presented here adopts the nomenclature originally put forth by Breder in [1]. Acceleration reaction is an inertial force, generated by the resistance of the changing water surrounding a body. Most fish generate thrust by bending their bodies into a backward-moving propulsive wave, which is called BCF locomotion. Other fish use their median and pectoral fins, which is termed MPF locomotion.

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 incredible flexibility, energy conservation capability and the ability of detecting the direction of ocean currents as well as advancing by their orientation abilities, more and more bio-mechanisms come to study the JET mode as motive power source for the biomimetic robot.

In order to study the motion characteristics and movement mechanism of real jellyfish, the researchers made every effort to carry on the study of jellyfish through all kinds of observation and experiments. Gladfelter [2] described in detail that the swimming motion process of jellyfish is 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.

Similar to real jellyfish, the motion of the robotic jellyfish is modeled with a momentum balance for an accelerating mechanism. Thomas L. Daniel [3] summarized that the model consists of four main terms, each of which corresponds to an instantaneous force produced by, or acting on the jellyfish. The model was expressed below.

$$\begin{aligned}\mathbf{T}hrust &= \mathbf{D}rag + \mathbf{A}cceleration\ reaction \\ &+\mathbf{F}orce\ to\ overcome\ inertia\ of\ animal\end{aligned}. \qquad (1)$$

McHenry *et al.* [4] tracked the movement of the ex-umbrellar and subumbrellar surfaces along the central axis and defined the bell margin as the ring of flexible tissue running from the distal margin of the bell to a proximal line of high bending. The morphometrics and hydrodynamic modeling are illustrated in Fig. 1. Sean P. Colin *et al.* [5] discovered that flexible bell margins were key components of rowing medusa morphologies and were expected to contribute towards their high propulsive efficiency. Jifeng Peng *et al.* [6] found that a more prolate-shaped swimmer with larger stroke amplitudes was able to swim faster, but its cost of locomotion was also higher. In contrast, a more oblate-shaped swimmer with smaller stroke amplitudes used less energy for its locomotion, but swam more slowly.

The researches on robotic jellyfish started relatively late. In recent ten years, moulding prototypes have been developed only in succession. At the beginning of the study, digital servo and mechanical joints need to occupy too large space. Yet conversely, smart actuators not only solve the problem above, but also meet the demand for contraction-relaxation motion. As a consequence, in the early researches for jet

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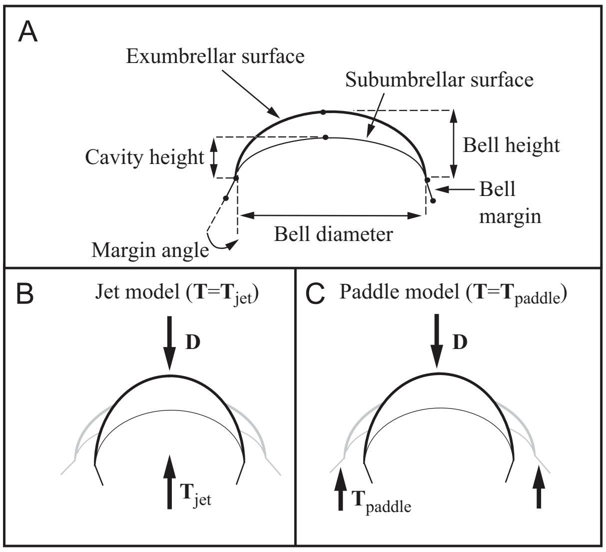

Fig. 1. Morphometrics and hydrodynamic modeling proposed by McHenry.

propulsion applying to underwater robots, smart actuators such as SMA (shape memory alloy), IPMC (ionic polymer metal composite), and EMA (electromagnetic actuation) are adopted prevailingly.

Alex Villanueva *et al.* [7] from Virginia Tech fabricated an robotic jellyfish called *Robojelly* which used bio-inspired SMA as actuators. *Robojelly* was 242 g in weight, 164 mm in bell diameter. Joseph Najem and Donald J. Leo [8] from Center of Intelligent Material Systems and Structures in Virginia Tech presented a biomimetic jellyfish robot that used IPMCs as flexible actuators for propulsion. The robotic jellyfish with four actuators swam at an average speed 0.77 mm/s and consumed 0.7 W. Youngho Ko *et al.* [9] from Chonnam National University in Korea proposed a jellyfish-like swimming mini-robot actuated by an EMA system in space. The body of the robot was 17 mm long and 0.5 mm thick. The EMA system was able to produce a uniform magnetic field to bend the fins of the jellyfish-like robot to generate thrust.

The researches on pure mechanical structure of the robotic jellyfish started only five years ago. Kenneth Marut [10] from Virginia Tech developed a large robotic jellyfish called *Cyro* in 2013. The full vehicle measures 170 cm in diameter and had a total mass of 76 kg. It achieved an average velocity of 8.47 cm/s, while consuming an average power of 70 W. Germany company FESTO proposed a robotic jellyfish called *AquaJelly*, it consisted of a transparent hemisphere and eight root power tentacles. Our Institute of Automation, Chinese Academy of Sciences [11] put forward a robotic jellyfish based on mechanical structure drive, it could accomplish jet propulsion, turning and snorkeling. Its maximum swimming speed was able to reach 80 mm/s.

Compared to *Cyro*, *AquaJelly* and the robotic jellyfish actuated by smart actuator, our robotic jellyfish is smaller, faster and can achieve much more mode. Nevertheless, the attitude and posture of previous edition of the robotic jellyfish are too stiff and limited. Consequently, we developed a novel robotic jellyfish based on mechanical structure drive and barycenter adjustment mechanism.

II. Mechanical Design

A. Bio-Inspired Configuration

The design inspiration of our robotic jellyfish is mainly derived from the imitation of *Aurelia aurita* (also called the moon jellyfish). *Aurelia aurita* is a widely studied species of the genus Aurelia. The jellyfish is translucent, usually about 25 cm to 40 cm in diameter and typically saucer-shaped or hemispherical. The bell-shaped mesogloea of it is commonly thick and of solid consistency, being thickest in the center of the umbrella [12].

Inspired by the *Aurelia aurita*, our robotic jellyfish is also hemispherical in shape. The robotic jellyfish consists of a bell-shaped rigid head, a tubbish main cavity and four six-bar linkage mechanisms. The bell-shaped rigid head is made of transparent plexiglass for consideration of simulating characteristics of lucency for *Aurelia aurita*. Beyond that, the selection of material plexiglass takes into account the installation of camera in the further experiments. Transparent medium will be propitious to imaging. The main cavity is made of white nylon and is hollow molding for placing the barycenter adjustment machanism, circuit board, communication module, battery and sensors. It is demonstrated in Fig. 2. As the actuation unit, the six-bar linkage mechanisms consist of a digital servo, a rocker, three bars, and a side link. Because of the limitation of the main cavity, four digital servos are put outside and assembled into specialized steering gear box. In order to imitate the umbrella-shaped mesogloea, a huge piece of latex skin is enwrapped around the actuators as showed in Fig. 3. Some parameters of the robotic jellyfish are listed in the table below.

TABLE I
Parameters of the robotic jellyfish

Unit	Material	Parameters
Head	plexiglass	242 mm (diameter) 89 mm (height)
Cavity	nylon	242 mm (diameter) 138 mm (height)
Limb	nylon	331 mm (length)
Gear box	nylon	66 mm (length) 46 mm (width) 29 mm (height)
Rocker	aluminium	80 mm (length)
Entirety	—	8.242 kg (weight)

For underwater robot, waterproofing problem is unavoidable. The robotic jellyfish is no exception. There are four spots require watertightness, three for still sealing and one for motive sealing. O-type sealing ring is adopted between the head and the cavity as well as steering gear box and cavity. Considering the area limitation, waterproofing rubber pad is utilized between the steering gear box and its cover. For motive sealing, framework oil seal is employed in output shaft to solve the motive waterproofing problem.

B. Barycenter Adjustment Mechanism

The swimming direction of the robotic jellyfish rests with the relative relationship of the orientation of the head and the

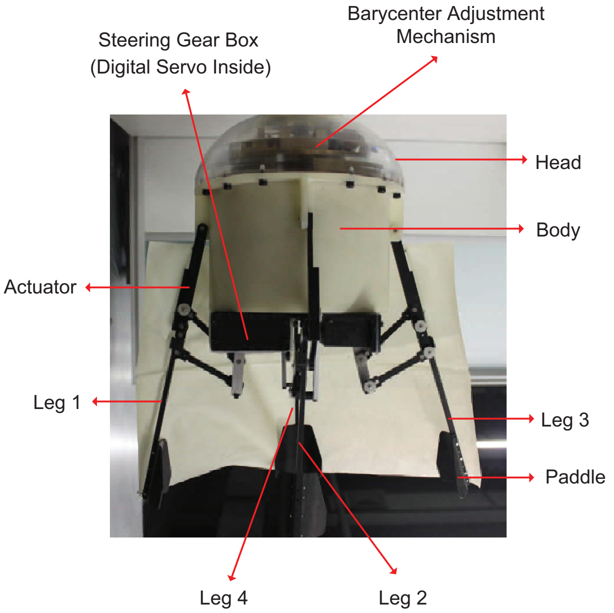

Fig. 2. Mechanical configuration of the robotic jellyfish with paddles.

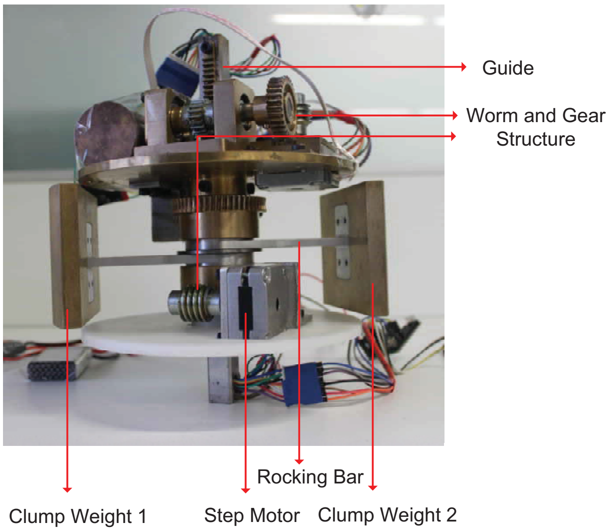

Fig. 4. Barycenter adjustment mechanism in equilibrium state.

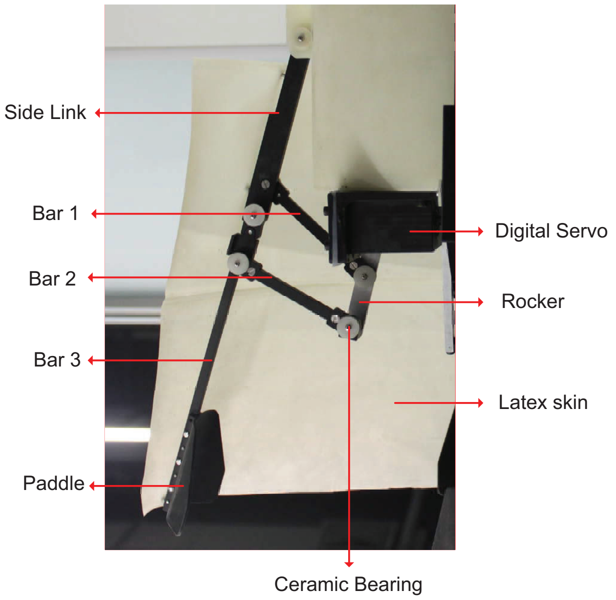

Fig. 3. Actuator part of the mechanical design of the robotic jellyfish.

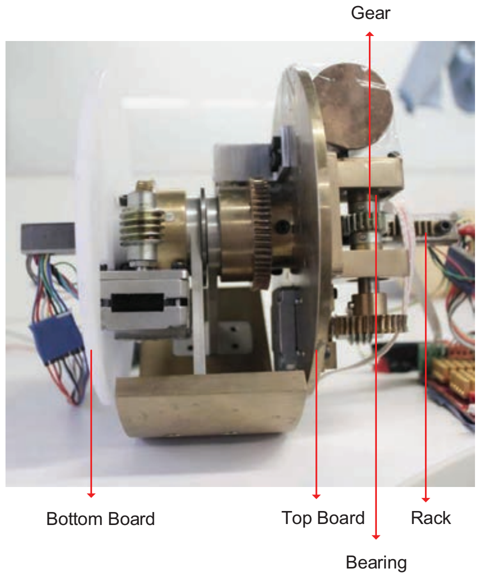

Fig. 5. Barycenter adjustment mechanism in partial inverted state.

driving force. Yet, the orientation of the head mainly depends on the relative position between the center of gravity and the center of buoyancy. The center of buoyancy will not be altered once prototype is formed. Hence, the orientation of the robotic jellyfish changes with the altering of the center of gravity. In our studies, we designed a unique barycenter adjustment mechanism so as to realize the function of barycenter 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 on two clump weights which are made of red copper and weigh one kilogram each. The clump weight is able to accomplish rising-descending movement in vertical direction and circular movement in horizontal plane. By the horizontal movement of the clump weight, the center of gravity can be shifted in the horizontal direction, and by the vertical movement of the clump weight, the center of gravity is able to changed in the vertical direction. Consequently, the center of gravity may altered in the horizontal and vertical direction, so that the locus of barycenter is able to enwrap the center of buoyancy.

The driving force actuating the movement of the clump weights comes from the output shaft drawing out from the step motor. 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.

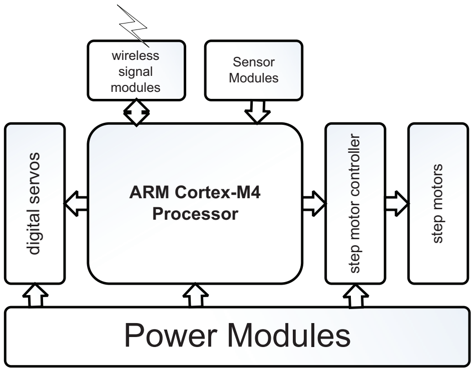

Fig. 6. Electronic circuit system of the developed robotic jellyfish.

III. Development of the Control System

A. Electronic Circuit Design

The electronic circuit system of the robotic jellyfish mainly consists of three circuit modules, main control chip, step motor control module and pull-up circuitry. STM32 processor serves as the control core of the robotic jellyfish and is applied in the main control chip. The processor has the characteristics of strong performance, rich interfaces, low power consumption, low cost and user-friendliness. The control chip is used to accomplish four tasks. It is needed to send PWM signals to drive digital servos and step motor controller, thus driving three step motors revolving. For connecting with the terminal, communication module fulfilled by RF200 is linked to the control chip. The communication module should not only accomplish the control signal receiving, but also achieve sending the position and attitude information signals acquired by sensors. Beyond that, battery module is necessary to supply the power to the control chip, step motor control module and digital servos. Port output voltage of the processor is 3.3 V, so the mode of it should be switched to open-drain output mode and pull-up resistances are added, which build up the pull-up circuitry. The demonstration is showed in Fig. 6.

B. Establishment of the Control Platform

To achieve closed-loop control of the robotic jellyfish underwater, it is necessary to create a platform so that the information flow and control flow can be transmitted and delivered on the platform. The control platform is divided into two parts, manager computer part and slave processor part. The two parts are connected by wireless signal modules. The manager computer is usually a personal computer that two ports are needed. One port is responsible for transmitting control signals to the slave processor via radio-frequency signal generated by transceiver module RF200, while the other port is to receive position and posture signal sent back from the slave processor via RF200. PC software will be used to process the received information and then display the results to the screen. Through the analysis to the position and orientation information, the center of gravity and the forward speed of the robotic jellyfish will be adjusted and changed. The decision-making instruction will be sent by means of manager computer software, through output port, wireless transmission module and then to the slave processor in the end.

The work flow for the slave processor part is similar with the manager computer part. Likewise, two ports are selected to connect two peripheral circuits, one is responsible for receiving radio-frequency signal coming from the PC, and the other is responsible for transferring the disposed attitude information and depth information signals of the robotic jellyfish coming from posture and pressure sensors to the manager computer using RF200. The control signals processed are sent to control the stepper motor controller for barycenter adjustment mechanism and digital servos for limbs to achieve changing attitude and position of the robotic jellyfish in water. At this point, the control platform with a closed network set up completely.

IV. Simulation for Barycenter System

In order to test whether the clump weights can accomplish the function desired, some calculation and simulation have to be conducted [13]. 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 expressed as

$$\mathbf{barycenter}_1 = (lsin\phi, h, lcos\phi)^T \tag{2}$$

Likewise, the coordinates of barycenter of clump weight two is

$$\mathbf{barycenter}_2 = (lsin\psi, h, lcos\psi)^T \tag{3}$$

The coordinates of horizontal component of the barycenter adjustment mechanism is

$$\mathbf{barycenter}_{ho} = \begin{pmatrix} \frac{l(sin\phi + sin\psi)}{2} \\ h \\ \frac{l(cos\phi + cos\psi)}{2} \end{pmatrix} \tag{4}$$

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.

In vertical direction, if the coordinates of barycenter of external cavity of the robotic jellyfish is expressed as

$$\mathbf{barycenter}_{ve} = (0, f, 0)^T \tag{5}$$

The coordinates of the barycenter of whole robotic jellyfish is

$$\mathbf{barycenter} = \begin{pmatrix} \frac{l(sin\phi + sin\psi)}{2} \\ \frac{hm_1 + fm_2}{m_1 + m_2} \\ \frac{l(cos\phi + cos\psi)}{2} \end{pmatrix} \tag{6}$$

where m_1 and m_2 are the mass of the barycenter adjustment mechanism and the external cavity of the robotic jellyfish

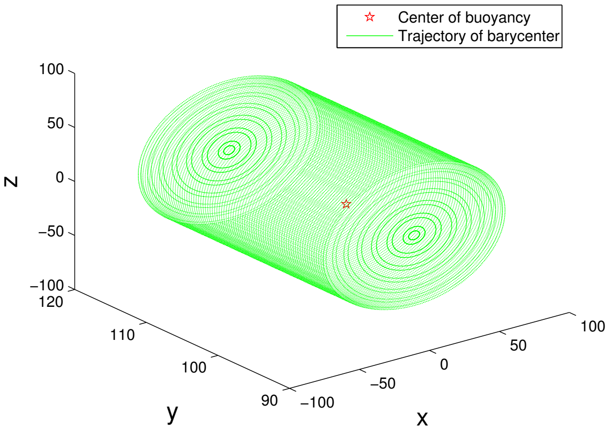

Fig. 7. Relationship between the change of barycenter and the position of the buoyancy center from 3D view (Locus contour of barycenter is only showed).

respectively. f is the y-coordinate of the barycenter of the external cavity of the robotic jellyfish.

By simulating in MATLAB (version 8.1; Mathworks), the relationship between the range of barycenter and the center of buoyancy is showed in Fig. 7. From figure, it is can be seen that the degree of deviation between barycenter and center of buoyancy which is sufficiently able to make the attitude of the robotic jellyfish transform freely on a spherical track.

V. Experiments and Results

In order to verify the robotic jellyfish, experiments are conducted iteratively. On the one hand, performance of the barycenter adjustment mechanism should be tested and it is guaranteed that the mechanism is able to work normal and well. On the other hand, operating of the barycenter adjustment mechanism and the contraction-relaxation jet propulsion motion of the four actuators should cooperate sufficiently so that the robotic jellyfish can locomote freely in the 3D space underwater.

Firstly, the capability of the barycenter adjustment mechanism is tested and verified. It is able to execute balance movement and lean-down movement in the horizontal direction as well as upward movement and downward movement in the vertical direction respectively. All experiments are implemented excellently and the video screen shots are shown in Figs. 8–11. Validated through experiments, the moving velocity of the the barycenter adjustment mechanism upward and downward in the vertical direction can reach 1.1 mm/s, moreover, the clump weight can cover 180 degrees in 20 s, which means that the angular velocity of the the barycenter adjustment mechanism for balancing and leaning-down in the horizontal direction can reach 9°/s.

Then, the ability of motion in 3D space is tested. Experiments showed that the robotic jellyfish could achieve swimming freely in 3D space like a real jellyfish and the direction the head could shifted and controlled as desired. Through the analysis to the video screenshot, the time of turning around from upside down pattern to head-on pattern is 30 s, which means that the velocity is able to reach 9°/s.

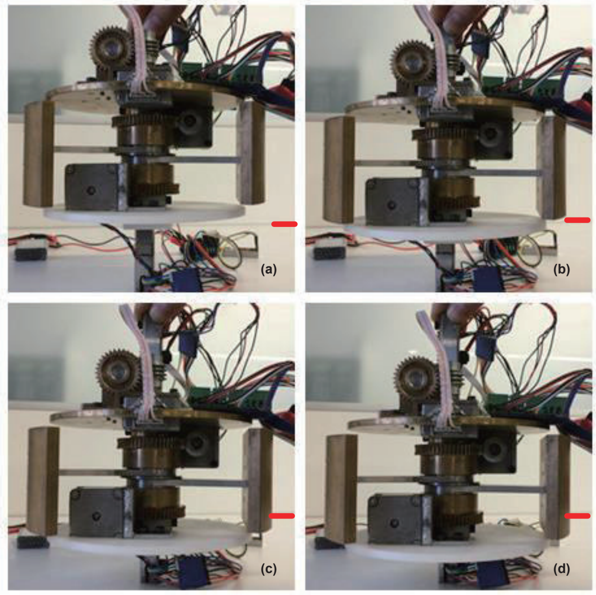

Fig. 8. Downward movement in the vertical direction of the barycenter adjustment mechanism. Note that a red line is placed as reference to better demonstrate the process of movement.

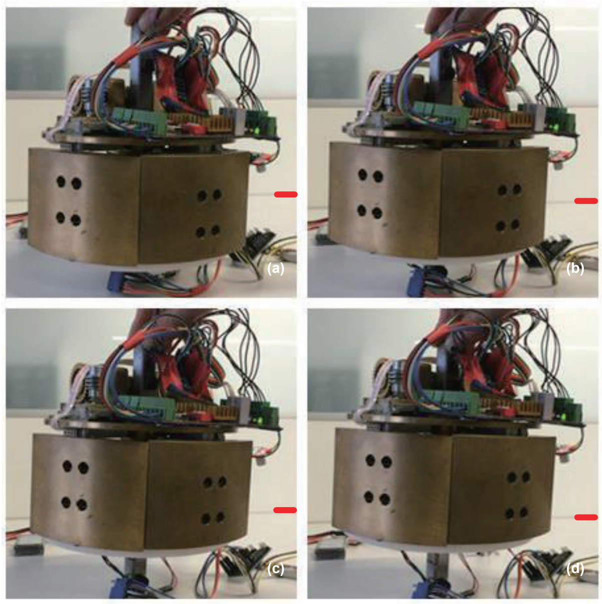

Fig. 9. Upward movement in the vertical direction of the barycenter adjustment mechanism. Note that a red line is placed as reference to better demonstrate the process of movement.

By further observations, the average swimming speed can attain 100 mm/s.

VI. Conclusion and Future Work

In this paper, we developed a novel self-propelled jellyfish robot based on mechanical structure drive and barycenter adjustment mechanism. Through the design and actualization of the noumenon and circuit of the robotic jellyfish, a jellyfish-like robot which is able to locomote in the water is developed. By means of calculation and simulation in

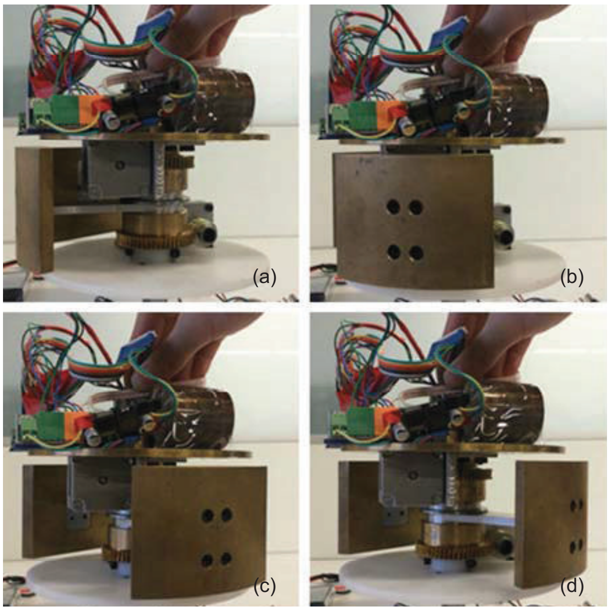

Fig. 10. Balance movement in the horizontal direction of the barycenter adjustment mechanism.

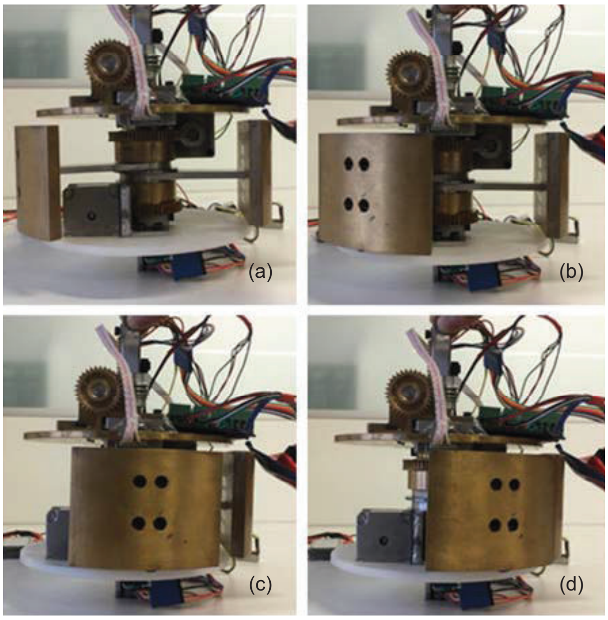

Fig. 11. Leaning-down movement in the horizontal direction of the barycenter adjustment mechanism.

the virtual environment, the ability and performance of the robotic jellyfish have been tested preliminarily. Furthermore, diversified experiments are conducted to verify the theory and simulation. It is shown that the robotic jellyfish can fulfill the motion in 3D underwater space. Modes among climbing, submergence, and leaning-down can switch freely. Attitude turning around velocity of the robotic jellyfish is able to reach 9°/s and the average swimming speed can attain 100 mm/s.

In the future, emphasis will be placed on how to make the robotic jellyfish change the attitude and posture more graciously and accurately. Once the motion of a single

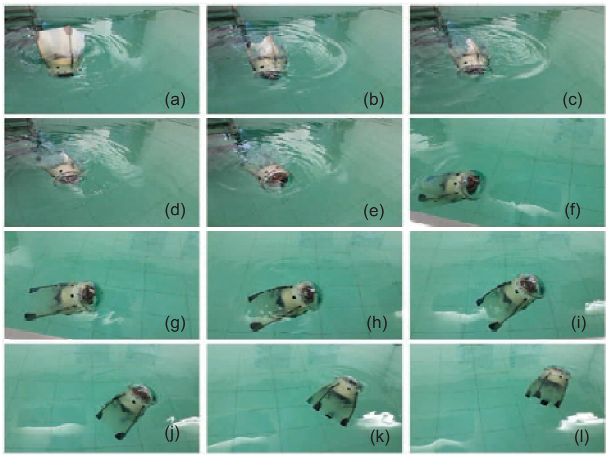

Fig. 12. The video screenshot of the novel robotic jellyfish swimming in 3D space.

robotic jellyfish is well behaved, a team of jellyfish will be investigated. In addition, for the purpose of building a mobile aquatic platform responsible for search and inspection, more practical aspects of jellyfish robots should be considered.

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