# Swimming Pattern Generator Based on Diving Beetles for Legged Underwater Robots

Hee-Joong Kim and Jihong Lee

*Abstract*—**In the paper, we propose a better solution with a view point of biomometic technique. As a biomimetic model of underwater organisms, we chose diving beetles structurally similar to a legged underwater robot Crabster which is under development. Various swimming locomotion of the diving beetle has been observed and sorted by robotics technology through experiments with a high-speed camera and image processing software Image J. Subsequently, we analyze coordinated patterns of rhythmic movements of the diving beetle. Through the procedure of comparing locomotion reproduced by simple control parameters with observed motions of the diving beetles, we confirmed applicability of various swimming patterns to the robot making it easy to control trajectories and velocities of its legs. In addition, the concept of the robot leg is proposed for efficient swimming.**

***Index Terms*—Diving beetles, bio-inspired legged underwater robots, swimming pattern generator, underwater locomotion.**

## I. Introduction

The research of swimming patterns based on biomimetics for underwater robots had been increased for the purpose of employing the agility and efficiency of animal locomotion. As the underwater organisms have been evolved to suit given environments for millions years, their capability to rapidly and continuously modulate locomotion by accelerating, decelerating, changing type of motion, and changing directions is enough to fascinate engineers. What is more interesting about mimicking living organisms in the water for carrying out some missions such as ocean detection and resource exploration is not only to grate dynamic characteristics but also to have higher energy efficiency more than the undersea robots which have propeller based actuators through many researches[1], [2].

Generally, most of the bio-inspired robots which are mainly focused on a task of ocean detection employed fish-like locomotion in forms of the repetitive swishing and oscillating fins of tails[3]-[6]. There is one of the well-known legged underwater robot, AQUA, it does not use-like stepping or retractable movements for its legs or feet as the legs move like wheels and paddles [7]. Unlike the research that mentioned above, the primary difference of our approach for underwater swimming is to develop an articulated-legged underwater robot called CRABSTER in order to perform many missions such as manipulation and collection while both walking and swimming. CRABSTER has been in development at KORDI (Korea Ocean Research & Development Institute) since in 2010 [8]-[10]. The walking type of CRABSTER called CR200 which is able to operate the depth of 200m underwater is officially released in 2013 (see Fig. 1).

Fig. 1. A bio-inspired legged underwater robot CRABSTER.

As designing a walking and swimming type of the robot for the next step, we have been studied on one of the legged underwater livings, a diving beetle, which is optimized for swimming in the water at any direction.

Fig. 2. A diving beetle (Cybister lateralimarginalis).

In this paper, we analyze its swimming patterns and confirm the possibility of applying its locomotion to the robot with the following procedures.

1) An experimental environment to analyze the diving beetle was set up with a high speed camera to get motion capture data of its movements. A model of its movements was generated through engineering techniques and the dynamic characteristics of the diving beetle were observed.

2) The pattern generator is developed for repetitive movements of the legged underwater robot inspired by diving beetle with simple control parameters.

3) It is verified that the motions of diving beetles are easily reconstructed with high similarities by comparing produced locomotion by adjusting the parameters with observed motions of the diving beetle.

4) The concept of the robot leg is proposed for efficient swimming considering the dimensional problem.

## II. Swimming Pattern Analysis of Diving Beetles

### A. An Experimental Environment

In order to observe the movement of the diving beetles closely, a high-speed motion capture system has been built up shown as Fig. 3. Diving beetles are swimming in the water

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tank, and a high-speed camera [11] recorded at rate of 125 frames per second mounted on the ground pointing to the bottom side of the water tank. A lamp was positioned to make the images clear and the recorded images are imported to a laptop computer.

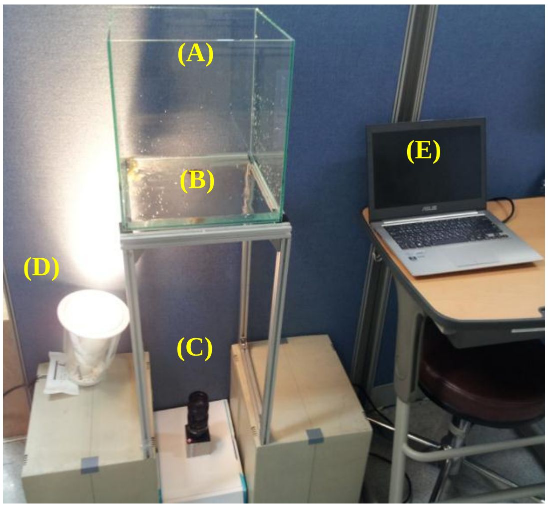



Fig. 3. A motion capture system - (A): A transparent water tank, (B) : Diving beetles, (C): A high-speed camera, (D): A lamp, (E) : A laptop computer.

The image sequences were dealt with the image processing software, Image J [12], frame by frame for obtaining angular values of each leg joint (see Fig. 4).

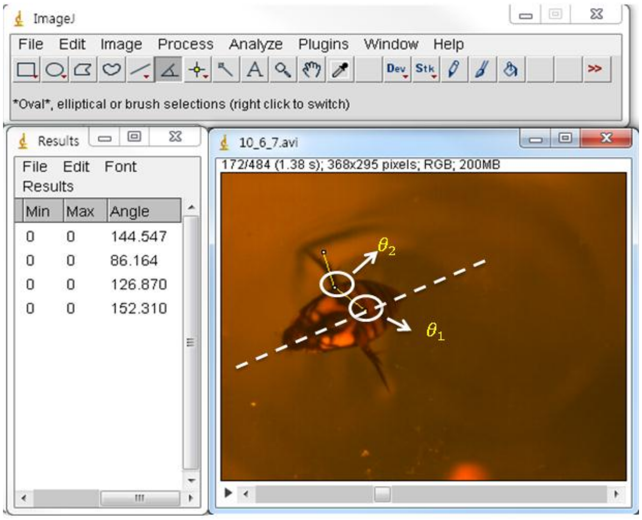



Fig. 4. Image processing by Image J to measure the joint angles on the leg of the diving beetle.

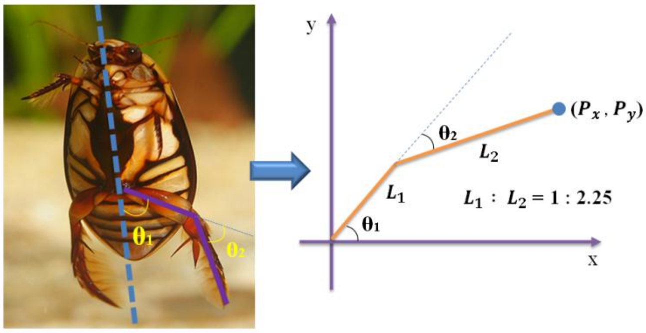



Fig. 5. An experimental environment for observing the locomotion of the diving beetle.

## B. *Classification of the Diving Beetle's Locomotion*

Diving beetles have six legs but through observation, we noticed that they mainly use hind legs for their movement while swimming. For this reason, we only focused on the motion of the hind legs. The leg of the diving beetle was simplified into two joints even it has passive flexibility on the second segment. The application of the passive joints will be depicted in Section IV for the robot design in the future. Geometric parameters for a two-linked leg are shown in Fig. 5 with forward kinematics.

TABLE I: D-H(DENAVIT-HARTENBERG) PARAMETERS

| Link$_i$ | $\theta_i$ | $\alpha_i$ | $d_i$ | $a_i$ |
|---|---|---|---|---|
| 1 | $\theta_1$ | 0 | 0 | $L_1$ |
| 2 | $\theta_2$ | 0 | 0 | $L_2$ |

Kinematic equations relating to the joint displacement $\theta_1$ and $\theta_2$ given by transformation equation matrix $A_0^1\ A_1^2$ from D-H parameters (see Table I) is shown in (1).

$$A_0^1 = \begin{bmatrix} \cos(\theta_1) & -\sin(\theta_1) & 0 & L_1 \times \cos(\theta_1) \\ \sin(\theta_1) & \cos(\theta_1) & 0 & L_1 \times \sin(\theta_1) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$A_1^2 = \begin{bmatrix} \cos(\theta_2) & -\sin(\theta_2) & 0 & L_2 \times \cos(\theta_2) \\ \sin(\theta_2) & \cos(\theta_2) & 0 & L_2 \times \sin(\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

Total transformation matrix $T_0^2$ including $R_0^2$ and $P_0^2$ which indicate orientation and end point$(P_x, P_y)$of the leg respectively is shown in (2).

$$T_0^2 = A_0^1 A_1^2 = \begin{bmatrix} R_0^2 & & & P_0^2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$R_0^2 = \begin{bmatrix} \cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (2)$$
$$P_0^2 = \begin{bmatrix} L_1 \times \cos(\theta_1) + L_2 \times \cos(\theta_1+\theta_2) \\ L_1 \times \sin(\theta_1) + L_2 \times \sin(\theta_1+\theta_2) \\ 0 \end{bmatrix}$$

We classified representative swimming patterns such as moving forward (see Fig. 6) and turning (see Fig. 7). All of the simulations with obtained data from experiments were performed in a two-dimensional workspace with Matlab.

# III. SWIMMING PATTERN GENERATOR

## A. *Set up Swimming Pattern Parameters*

Through the observation of the diving beetle's locomotion, coordinated patterns of rhythmic movements were confirmed with the forms of a sinusoid on each joint of the leg. In order to design a pattern generator incorporating engineering techniques based on the phenomenon mentioned above, lest-squares fit was applied to the obtained the sinusoidal data from the experiments.

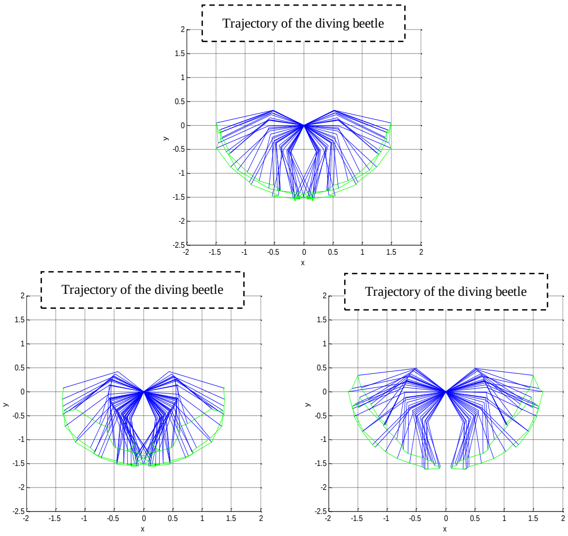



Fig. 6. Observed forward swimming motions of the diving beetle.

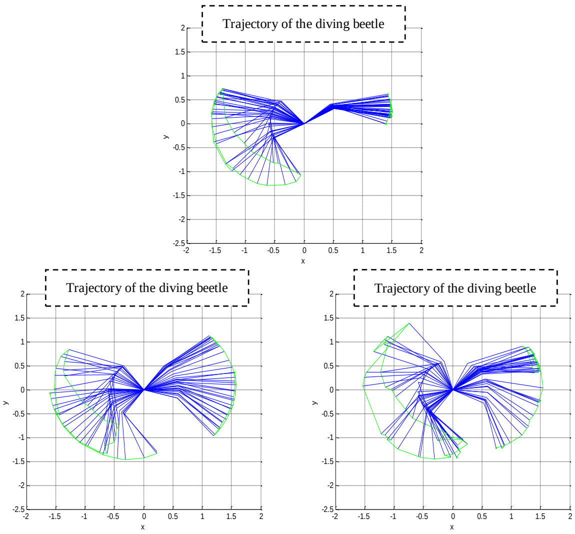



Fig. 7. Observed turning swimming motions of the diving beetle.

The objective is to determine coefficient values that minimize $S_r$ in (3) with the known factors such as $y_t$(obtained joint angular data), $N$(the number of the data), $t$(sampling time = 0.01s), and $f$(frequency 1/T=1/0.28s).

$$S_r = \sum_{i=1}^{N} \{y_t - [A_0 + A_1 \cos(\omega t) + B_1 \sin(\omega t)]\}^2, \omega = 2\pi f \quad (3)$$

To solve the unknown coefficients, the equations are expressed as (4).

$$A_0 = \frac{\sum y_t}{N}, A_1 = \frac{2}{N}\sum y_t \cos(\omega t), B_1 = \frac{2}{N}\sum y_t \sin(\omega t) \quad (4)$$

The model can also be expressed making one coefficient less in the format of (6) by calculating (5).

$$\theta = \operatorname{artan}\left(\frac{B_1}{A_1}\right), C_1 = \sqrt{{A_1}^2 + {B_1}^2} \quad (5)$$

$$y = A_0 + C_1 \cos(\omega t + \theta) \quad (6)$$

For making various patterns by the given equation (6), controllable parameters were applied to (6) as (7) and (8) to understand characteristics of coefficients when diving beetles are swimming.

$$\theta_1 = y_{joint1} = U_1 A_0 + U_2 C_1 \cos(\omega k_1 t + \theta + \varphi_1) \quad (7)$$

$$\theta_2 = y_{joint2} = U_{11} A_0 + U_{22} C_1 \cos(\omega k_2 t + \theta + \varphi_2) \quad (8)$$

### *B. Characteristics of Each Determined Parameter on a Leg Trajectory*

For demonstrating the characteristics of four parameters of the designed pattern generator, we examined variations of the leg trajectories closely according to changing values of the parameters. Activating regions of each parameter are shown in Fig. 8. The parameters, $k_1$ and $k_2$ are not remarked on Fig. 8 as they are in charge of the velocity of the periodic motion. Furthermore, one of the parameters $\varphi_1$ on the first joint of the leg is not listed either since the first joint is always moving ahead before the second travels.

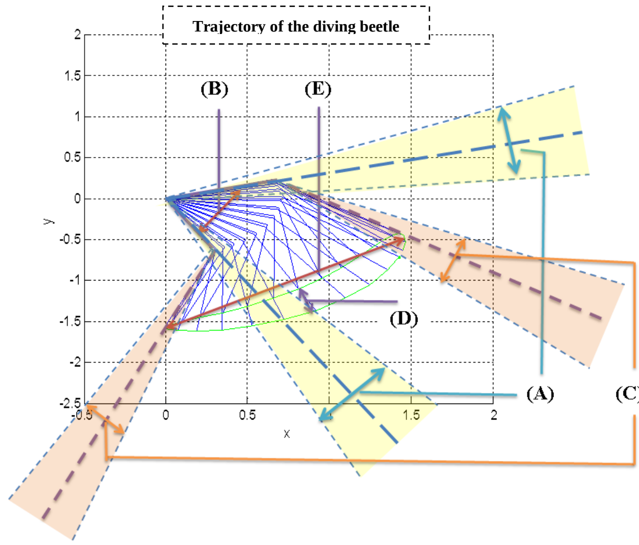



Fig. 8. Parameter characteristics adjusting leg trajectory - (A) : $U_1$, (B) : $U_2$, (C) : $U_{11}$, (D) : $U_{22}$, (E) : $\varphi_2$.

The characteristics of the control parameters of the leg trajectory and velocity are depicted in Table based on Fig. 8.

TABLE II: CHARACTERISTICS OF DETERMINED PARAMETERS

| Parameters | Characteristics |
|---|---|
| $U_1, U_{11}$ | ▪ Constant values for offset.<br>▪ It determined moving range of the leg trajectories. |
| $U_2, U_{22}$ | ▪ Constant values for amplitude.<br>▪ It determined sizes of the leg trajectories. |
| $k_1, k_2$ | ▪ Constant values for frequency.<br>▪ It determined the velocities of the leg. |
| $\varphi_1, \varphi_2$ | ▪ Constant values for phase delay.<br>▪ It changes leg trajectory by adjusting phase interval of $\theta_1$ and $\theta_2$ of the leg. |

### *C. Comparison between the Diving Beetle and Regenerated Locomotion by Parameter Setting*

To control the legged underwater robot, it is necessary to verify the generated locomotion by the pattern generator. For the solution of this matter, we compared produced locomotion with observed motions of the diving beetle. According to different locomotion, the parameters are set with proper values considered by each characteristic (see Table III).

TABLE III: PARAMETER SETTING FOR VARIOUS LOCOMOTION

| Swimming Locomotion | $\theta_1$ | | | | $\theta_2$ | | | |
|---|---|---|---|---|---|---|---|---|
| | $U_{1,}$ | $U_{2,}$ | $\varphi_{1,}$ | $k_{1,}$ | $U_{11,}$ | $U_{22,}$ | $\varphi_{2,}$ | $k_{2,}$ |
| **1** | 1 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| **2** | -0.5 | 1.1 | 0 | 1 | 1.3 | 2.5 | π/4 | 1 |
| **3** | -0.7 | 1.3 | 0 | 1 | 0.9 | 2.5 | π /4 | 1 |
| **4** | 0.3 | 1.2 | 0 | 1.6 | 1.4 | 1.9 | 0 | 1.6 |
| **5** | 0.7 | 0.85 | 0 | 1.2 | 1.2 | 0.9 | π /6 | 1.2 |
| **6** | -1.7 | 0.15 | 0 | 0.7 | 0.7 | 0.4 | π /3 | 0.7 |

Fig. 9 shows a parameter space on the basis of the determined values of the parameters. Application of this parameter space by considering relationships of each factor on x-y axes thoroughly is expected to reduce the number of parameters which means to control the robot more efficiently.

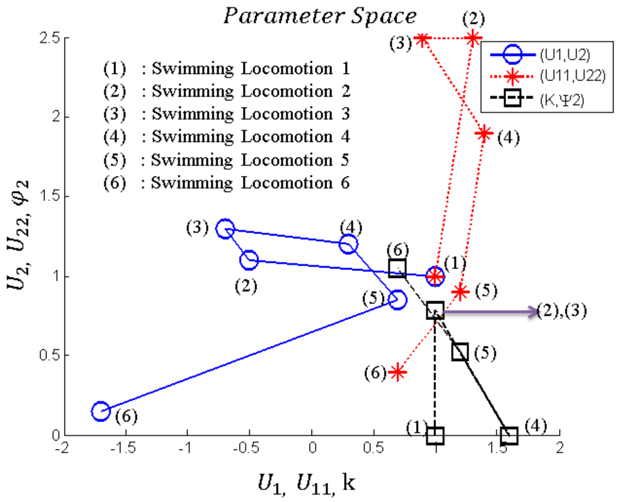
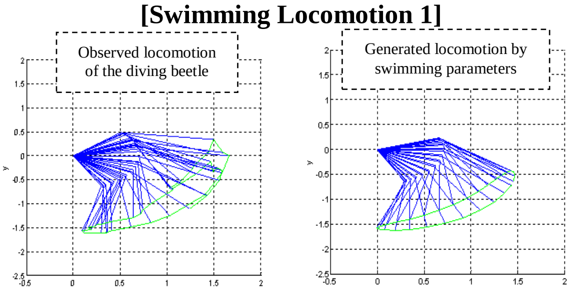



Fig. 9. Parameter space.

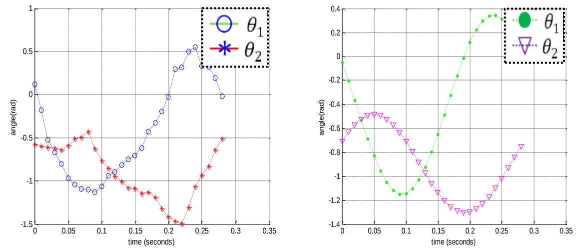
Six representative trajectories and joint-angular changes of classified swimming motions of the diving beetles are shown on the left side in Fig. 10. On the right side of the Fig. 10 indicates the locomotion by adjusting the parameters in which Table III states.

In spite of the fact that there is no such an intelligent system as living organisms do perfectly, the results in Fig. 10 represent that the way of swimming from diving beetles were analyzed through this research and adjusting the determined parameters could make it possible to generate motions of diving beetles easily with high similarities.

**[Swimming Locomotion 1]**

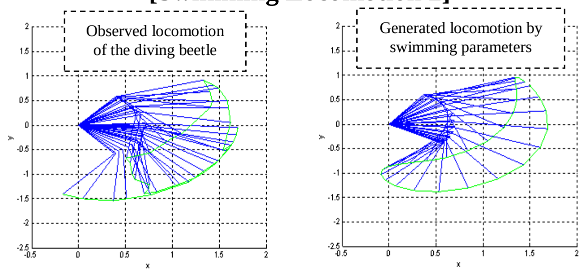



(a) Comparison of leg trajectories.

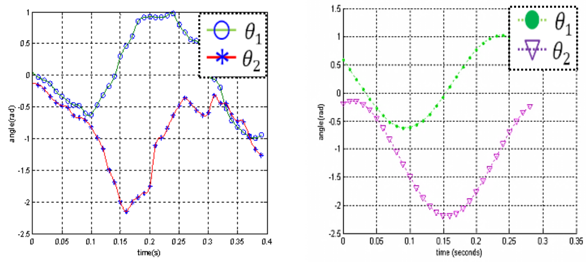



(b) Comparison of joint–anglular phases.

**[Swimming Locomotion 2]**

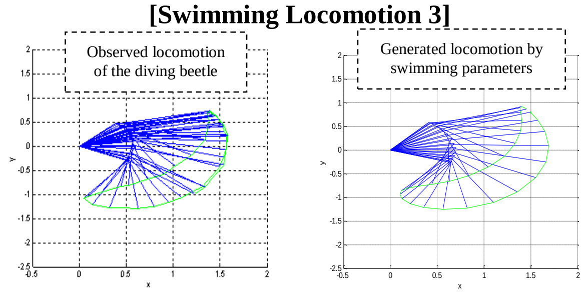



(a) Comparison of leg trajectories.

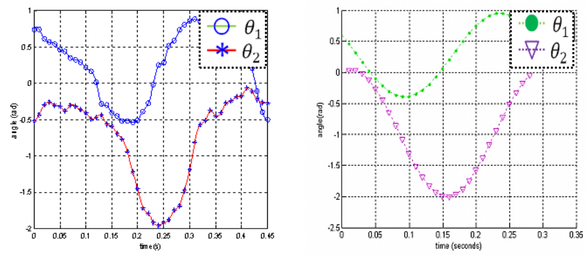



(b) Comparison of joint–anglular phases.

**[Swimming Locomotion 3]**

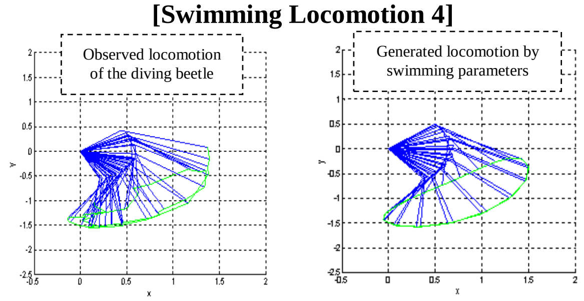



(a) Comparison of leg trajectories.

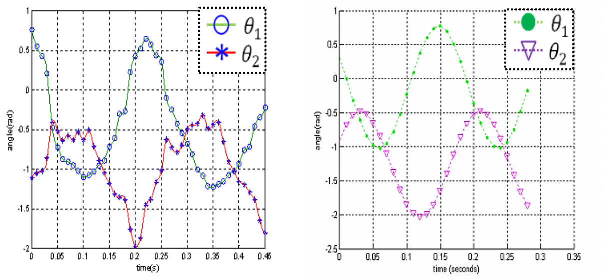



(b) Comparison of joint–anglular phases.

**[Swimming Locomotion 4]**

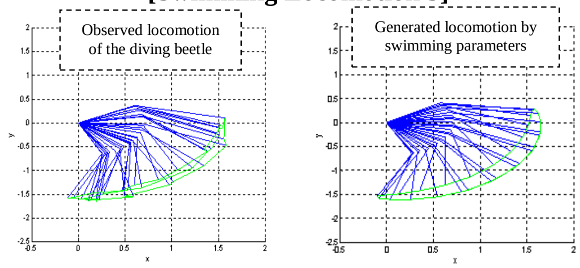



(a) Comparison of leg trajectories.

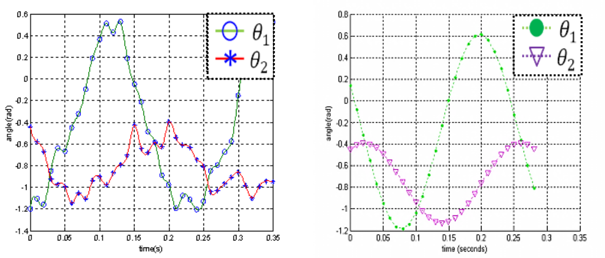


(b) Comparison of joint–angular phases.

**[Swimming Locomotion 5]**

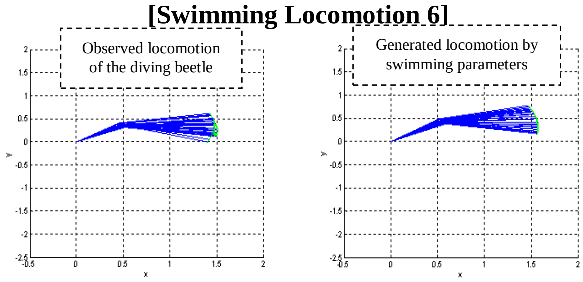



(a) Comparison of leg trajectories.

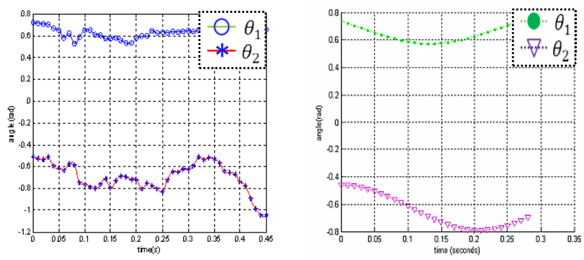


(b) Comparison of joint–angular phases.

**[Swimming Locomotion 6]**




(a) Comparison of leg trajectories.



(b) Comparison of joint–angle phases.

Fig. 10. Comparison of swimming locomotion generated by determined parameters with observed the motions of the diving beetle.

## IV. A Concept of Leg Design

### A. Kinematic Modeling for Leg Movements in 3-Dimension

The leg movements inspired by diving beetles are performed in two-dimensional space. However, it is essential to enlarge the dimension to three for underwater swimming of the robot. For having better solutions about this matter, we approach it by proposing a concept of the leg which is possible to both walk and swim. As a joint for hip pitch allows the robot to swim with the designed parameter generator, it is expected that the problem of three-dimensional movements of the robot could be easily solved (see Fig. 11).

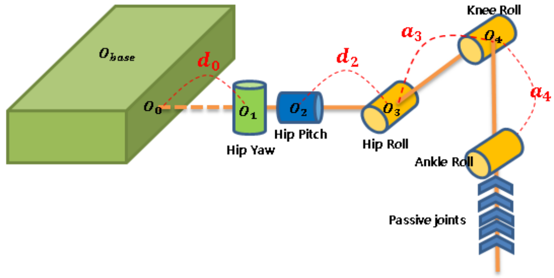



Fig. 11. Kinematic modeling of the leg.

D-H parameters for the kinematic modeling of the proposed design of the leg are described in Table IV.

TABLE IV: D-H (Denavit-Hartenberg) Parameters

| $Link_i$ | $\theta_i$ | $\alpha_i$ | $d_i$ | $a_i$ |
|---|---|---|---|---|
| 1 | 0 | 90 | $d_0$ | 0 |
| 2 | $\theta_1$ | -90 | 0 | 0 |
| 3 | $90+\theta_2$ | 90 | $d_2$ | 0 |
| 4 | $90+\theta_3$ | 0 | 0 | $a_3$ |
| 5 | $\theta_4$ | 0 | 0 | $a_4$ |

### B. Consideration for Passive Joints

As previously stated about the behavioral characteristics of the diving beetle, it mainly uses its two hind legs when swimming. We observed an interesting fact concerning its leg structure related to propulsion by studying the locomotion of the diving beetle.

The second segment is composed of many small, passive joints which flex while swimming (see Fig. 12). This flexibility was suspected to assist in more efficient propulsion. This was verified in [13] which referred to the propulsion of a robot inspired by an octopus. (A) and (B) in Fig. 12 indicate minimum and maximum angular limits of the passive joint and (C) shows the total number of passive joint-segments. Angular limits of each segment during power and recovery strokes can be calculated $6^\circ$ and $22^\circ$ respectively by dividing the angular limits into the number of the passive segments.

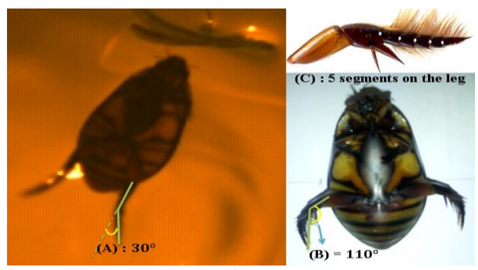



Fig. 12. Leg travel of the passive segments.

## V. Conclusion

Our study provides the first verification that sorted swimming patterns from diving beetles by motion capture based experiments are applicable to swimming robots in terms of biomimetics. It means that we take advantage of natural experiences from creatures which have changed themselves to suit their given environments on the Earth for millions of years.

The pattern generator is designed for repetitive movements of the legged underwater robot with simple control parameters. Each characteristic of the parameter was stated in the paper having different activating region on the leg trajectory. Then, each produced pattern was compared to observed motions of the diving beetle. As a result, the designed pattern generator could make it possible to produce motions of diving beetles easily with high similarities.

In addition, we proposed a concept of the leg which is possible to both walk and swim in three-dimensional space employing the benefit of the passive joints based on the leg structure of the diving beetle.

## ACKNOWLEDGMENT

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