Designing Diving Beetle Inspired Underwater Robot (D.BeeBot)

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Abstract—In the paper, designing process of a walking and swimming legged underwater robot is proposed. The robot has been inspired by diving beetles. To maximize swimming ability of the robot, the structural analysis of the diving beetle's leg has been conducted. The final model of the robot designed by AutoCAD(2D and 3D computer aided design) is presented based on employing structural advantages which diving beetles have. Additionally, underwater experiments with the designed robot leg has been implemented. Bio-mimicking swimming locomotion was applied to the robot leg during the experiments.

Keywords—diving beetles, bio-inspired legged underwater robot, motion planning

I. INTRODUCTION

In these days, a lot of researchers have been fascinated to develop underwater robots to conduct various missions such as detecting shipwrecks, natural resources and so on instead of humans in the hazardous environment. KRISO(Korea Research Institute of Ships and Ocean engineering) has successively developed a legged underwater robot CRABSTER(CR200) shown as (a) in Fig. 1 since 2010[1-4]. It was inspired by underwater organisms a crab and a lobster. It has been designed to avoid strong tidal current by changing the posture of the robot with legs as the crab and lobster do. It is also good for securing visibility from floating dust which the other vehicles operated by propellers or caterpillar cause while moving. Furthermore, manipulators are equipped with its two front legs to carry out various underwater missions on the seabed. The final goal of this robot is to have abilities of walking and swimming in the water up to 6,000m depth.

As one of cooperating institute of this project, we have been investigated into developing swimming technology of the legged underwater robot. We approached this matter in terms of biomimetics. Diving beetles(see (b) in Fig. 1) were chosen as a model for it and the research was started from analyzing and classifying their motions[5]. Subsequently, we were successfully designed the method called SPG(Swimming Pattern Generator) to mimic locomotion of the diving beetle with control parameters[6]. In order to test generated motions, we started to design a robot considering kinematic modeling of the robot leg to make it possible to both walk and swim. In addition, correct motors and gears which can cover enough force and speed, maximum required torques on each joint of the leg were selected by simple static and dynamic force analysis[7].

![Figure 1. CR200(a) and diving beetles(Cybister lateralimarginalis)(b).](image)

In the paper, we focus on the following statements.

1) Detailed features of the finalized model are presented. Robot legs are designed by considering structural advantages that the diving beetle has on its legs for effective swimming. Furthermore, auxiliary sensors to enhance the performance of the robot leg are introduce.

2) A body of the robot is designed and assembled with six legs. The name of this robot is CALEB 10(D.BeeBot : diving beetle inspired underwater robot).

3) The method(SPG) to generate various bio-mimicking locomotion is briefly summed up. A parameter space is defined and reorganised depending on results from underwater experiments with the robot leg.

II. MECHANICAL DESIGN OF THE ROBOT

In this chapter, structural analysis of the diving beetle’s leg as it has some advantages to maximize its propulsion. There are mainly two structural advantages for their effective swimming and they are applied to designing robot legs.
A. Structural analysis of a diving beetle’s leg

Diving beetles are mainly using their hind legs to generate propulsion for their swimming. They are relatively bigger and stronger than other four front legs. Therefore, we have focused on the hind legs to classify and analyze the swimming motion of the diving beetles. During the research for designing SPG(Swimming Pattern Generator) mimicking the locomotion of the diving beetle[6], structures of the diving beetle’s leg been closely examined. As a result, two structural advantages are founded as follows.

1) Bristles: A lot of bristles are placed on the last link of the diving beetle’s leg as shown in Fig. 2. The bristles are foldable passively, changing cross sectional areas against the water. This structure can maximize propulsion and reduce the water resistance during the power stroke and recovery stroke respectively.

2) Passive joints: Five segments, passively moving in the water, are attached to the leg of the diving beetle(Fig. 3). These have limited moving angles at each stroking period. Through an image processing tool(Image J), the angular movement of the passive joints has been observed as presented in Fig.3. This structure is working for similar effect as bristles have in the water. The efficiency of this mechanism was found and verified through the research about legs of octopuses[8].

In order to make the robot have not only walking mode but also three dimensional movements during swimming mode, the kinematic modeling of the robot is proposed in Fig. 4. Swimming motions are performed by hip roll and knee roll joints, and a hip yaw joint is in charge of mostly walking motions. Detailed features of the robot leg where the structural advantages of the diving beetle’s leg are applied are described in the next section.

B. Designing robot legs

Based on the proposed kinematic modeling in Fig. 4, detailed designing features of the robot leg is presented in Fig. 5 by considering structural analysis of the diving beetle’s leg. A hinged structure and flexible passive joints are corresponding to structural advantages(bristles & passive joints) diving beetles have. They are working passively against the water flow to have better swimming efficiency. Flexible passive joint-mechanism is carried out by a motor installed at the edge of the last link of the robot leg. It is designed to be able to adjust angular travels of each segment in both directions. The rotary motion of the motor is converted to the linear motion to have movements of sliding in and out according to walking and swimming modes of the robot.
More specifically, both mechanisms are working as shown in Fig. 6. The motion of the robot leg is from one of the biomimicking locomotion. During the power stroke (1→3) the flexible joints have smaller movement and the hinged structure is closed against the water to have maximal prolusion. In contrast, both mechanisms are working oppositely during the recovery stroke (4→6) to reduce water resistance. The performances of the robot leg were verified through underwater experiments in the previous work[9].

![Figure 6. Performance of the robot leg.](image)

Since the mechanism for passive joints has been designed to have sliding motion along the robot leg during mode conversion between walking and swimming, an automatic switching logic is required for working in the water. For this reason, a hall effect sensor(WSH138-XPAN2) which can read the magnetic fields has selected and placed both ends of the sliding path and magnets are installed on the way of the sliding motion. Fig. 7 shows implementation of the mechanism in the air.

![Figure 7. Implementation of the passive joints mechanism.](image)

The legs of the robot are six in total. There are two types which have different applications. Type 1 is designed for front four legs without flexible passive joints. The front legs are mostly changing the moving direction and supporting the propulsion that hind legs(Type2) produce. Therefore the front legs are shorter than the hind legs as depicted in Fig. 8.

![Figure 8. Leg dimension.](image)

Instead of making whole legs waterproof, only joints of the leg are sealed. It can not only reduce the weight of the robot but also improve maintainability. Each joint module which consists of a motor and a gear is placed in a cylinder shaped container with mechanical seal depicted in Fig. 9.

![Figure 9. Joint module of the robot leg.](image)

Each joint module has a multi-home positioning mechanism. On the clamp of the output shaft, a gradient tape (black to gray) is attached with a light sensor(SG-105F) as described in Fig.10. The sensor reads colored information on the gradient tape as the joint is moving. By using it, the joint can be returned to the desired position from any posture.

![Figure 10. Multi-home positioning system.](image)
C. Robot assembly

Housing electronic devices of the robot is an important issue to control the legs. Fig. 11 shows two types of controller housings. Type 1 includes a main controller, switching controller for passive joint-mechanism and a power distribution module. Furthermore, motor controllers and a multi-home positioning controller are contained in type 2.

Controller housings and hip pitch joints are placed on the body frame as depicted in Fig. 12. (1), (4) and (7) are hip pitch joints. (3) is a controller housing type 1. (2), (5) and (6) indicate controller housing type 2. Additionally, attachment points of six legs and body dimension are described in Fig. 12.

Fig. 13 shows an assembled robot CALEB 10(D.BeeBot : diving beetle inspired robot) without a body cover. The body cover will be designed by considering weight of the robot in the water to keep slightly negative buoyancy. Later, a controller to adjust buoyancy of the robot will be added.

III. SWIMMING LOCOMOTION

In the previous study, a method to mimic locomotion of the diving beetle was proposed[6]. In this chapter, the method called SPG(Swimming Pattern Generator) is briefly introduced. Furthermore, underwater experiments have been implemented with the locomotion produced by SPG.

A. Swimming pattern generation

In order to design SPG, Fourier least-squares fit was applied to the obtained the sinusoidal data obtained by motion-capture system[5]. As a result, unknown factors such as \( A_0, C_1, \theta \) in (1) and (2) were computed. Additionally, \( \omega \) (frequency) and \( t \) (sampling time) were set to 11 and 0.02s respectively. Based on equations of each joint, controllable parameters \( U_1, M_1, K_1 \) and \( \Psi_i \) were set in (1) and (2) to understand characteristics of each term.

\[
\theta_1 = y_{\text{joint1}} = U_1A_0 + M_1C_1\cos(\omega_1t + \theta + \Psi_1) \tag{1}
\]

\[
\theta_2 = y_{\text{joint2}} = U_2A_0 + M_2C_1\cos(\omega_2t + \theta + \Psi_2) \tag{2}
\]

As changing the values of determined parameters, activated regions were found as shown in Fig. 14. The parameters, \( k_1 \) and \( k_2 \) are not shown in Fig. 14 since they are in charge of the

TABLE I. RANGE OF MOTION

<table>
<thead>
<tr>
<th>Joints</th>
<th>Range of motion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hip pitch</td>
<td>(-150^\circ ) to (+150^\circ)</td>
</tr>
<tr>
<td>Hip yaw</td>
<td>Type 1 (-95^\circ ) to (+95^\circ)</td>
</tr>
<tr>
<td></td>
<td>Type 2 (-60^\circ ) to (+60^\circ)</td>
</tr>
<tr>
<td>Hip roll</td>
<td>Walking (-27^\circ ) to (+105^\circ)</td>
</tr>
<tr>
<td></td>
<td>Swimming (-30^\circ ) to (+60^\circ)</td>
</tr>
<tr>
<td>Knee roll</td>
<td>Walking (-160^\circ ) to (+70^\circ)</td>
</tr>
<tr>
<td></td>
<td>Swimming (0^\circ ) to (+135^\circ)</td>
</tr>
<tr>
<td>Passive joint</td>
<td>Swimming (6^\circ ) (power stroke)</td>
</tr>
<tr>
<td>(per segment)</td>
<td>(adjustable) (22^\circ ) (recovery stroke)</td>
</tr>
</tbody>
</table>
velocity of the periodic motion. A parameter $\Psi_1$ is also not appeared either because the first joint is always moving ahead compared to the second joint.

![Figure 14. Activated regions of determined parameters on the leg trajectory.](image)

Figure 14. Activated regions of determined parameters on the leg trajectory - (A) : $U_1$, (B) : $U_2$, (C) : $M_1$, (D) : $M_2$, (E) : $\Psi_2$.

The characteristics of determined parameters are stated in Table II.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_1, U_2$</td>
<td>$\bullet$ Constant values for offset.</td>
</tr>
<tr>
<td>$\Psi_1, \Psi_2$</td>
<td>$\bullet$ It determined moving range of the leg trajectories.</td>
</tr>
<tr>
<td>$M_1, M_2$</td>
<td>$\bullet$ Constant values for amplitude.</td>
</tr>
<tr>
<td>$k_1, k_2$</td>
<td>$\bullet$ Constant values for frequency.</td>
</tr>
</tbody>
</table>

$\bullet$ It determined the velocities of the leg.

$\bullet$ It changes leg trajectory by adjusting phase interval of $\theta_1$ and $\theta_2$ of the leg.

### TABLE II. CHARACTERISTIC OF DETERMINED PARAMETERS

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<td>$U_1, U_2$</td>
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</tbody>
</table>

$\bullet$ It determined the velocities of the leg.

$\bullet$ It changes leg trajectory by adjusting phase interval of $\theta_1$ and $\theta_2$ of the leg.

### B. Underwater experiments

By adjusting the values of the parameters as stated in Table III, six swimming motions are generated to mimic the observed representative locomotion of the diving beetle. It is confirmed that designed SPG can successively produce bio-mimicking motions(Fig. 15).

<table>
<thead>
<tr>
<th>Locomotion</th>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_1, M_1, k_1, \Psi_1, U_2, M_2, k_2, \Psi_2$</td>
<td>$\Psi_1, \Psi_2$</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1 1 0</td>
</tr>
<tr>
<td>2</td>
<td>-0.5</td>
<td>1 1 0</td>
</tr>
<tr>
<td>3</td>
<td>-0.7</td>
<td>0.9 1 0</td>
</tr>
<tr>
<td>4</td>
<td>0.3</td>
<td>1.2 1.6 0</td>
</tr>
<tr>
<td>5</td>
<td>0.7</td>
<td>1.2 1.2 0</td>
</tr>
<tr>
<td>6</td>
<td>-1.7</td>
<td>0.15 0.7 0</td>
</tr>
</tbody>
</table>

A force/torque sensor(Delta DAQ Transducer by ATI industrial automation) is installed at the end of the robot leg to measure directional forces(Fig. 16). It can measure directional forces while the robot leg is moving in the water based on the locomotion shown in Fig. 15. The experiments have been conducted without having the passive joints and hinged worked only to compare drag forces that each motion can generate.

![Figure 16. Experimental set up.](image)
X-directional measured data in Fig. 17 are the drag forces against the moving direction of the robot leg in the water.

Consequently, activated regions corresponding to the motion of each joint are discovered. With this phenomenon, a research of motion planning in the parameter space will be carried out as an extended study to simply produce various swimming motions.

IV. CONCLUSION

In this paper, detailed designing features of the robot are introduced. The robot has been designed to both walk and swim in the water with its six legs. More specifically, functions of the robot leg inspired by structural advantages of the diving beetle’s leg have been described. Subsequently, designing a body with controller housings is described to assemble six legs to it. Additionally, SPG(swimming pattern generator) has been briefly summed up from our previous work. Experiments have been implemented to measure drag forces of the robot leg while moving in the water with the produced bio-mimicking locomotion by SPG. As a result, the motions are listed in order by comparing the magnitude of drag forces along x-axis which is the moving direction of the robot leg. With this, the marks indicating information of different motions are reorganized in the parameter space and activated regions of each joint are discovered.

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REFERENCES


