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Construction of a Brain-machine Hybrid System to Analyze Adaptive Behavior of Silkworm Moth

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***Abstract*— We have created a brain-machine hybrid system (BMHS) which is able to solve the chemical plume tracking (CPT) problem using the brain of the male silkworm moth. The purpose of the system is to investigate adaptability which results from interactions between brain, body, and environment. In this paper, we describe a BMHS architecture and experiments to verify that the behavior of the BMHS is similar to that of a silkworm moth. The BMHS is a kind of cyborg system in which the body of a living being is replaced by a mobile robot and the organism's brain is used to control the robot. The artificial body is controlled by motor commands for the original body that are extracted from a signal recorded from the brain. For that purpose, a small measurement system to record signals was created and a method to reconstruct the motor commands from the signals was established. We demonstrate that the BMHS can behave like a silkworm moth. We compared the trajectories of moths with the trajectories of the BMHS incorporating the same individual moths. Through the experiments we confirmed that the system can solve the CPT problem. Our system has the potential to reveal principles of adaptability in silkworm moth behavior.**

I. INTRODUCTION

Recently, robots are expected to become a new labor power due to the shrinkage of the labor force from the falling birthrate and the aging population. However, current robots have little capability to operate under the dynamically changing environments, thus the scope of their tasks is limited to the supposed conditions from design stage.

In contrast, living beings live in variable environments, and accomplish numerous tasks. Understanding the principle of this ability to adapt to changing environments, which we call adaptability, is necessary in order to implement the analogous features into the robots. Furthermore, it is expected to become the breakthrough for understanding brain functions.

This adaptability is considered to be a result of complex interactions between brain, body, and environment. Therefore, it is difficult to understand the principle of adaptability by using methods employed in the field of brain science only. The difficulty is increased by the prerequisite condition for studying the brain, that is the measurement of the brain usually requires static and stable conditions of it.

To overcome these restrictions, a new experimental technique is needed for dynamic measurements. We propose a brain-machine hybrid system (BMHS) that will allow a better understanding of the interactions between brain, body, and environment[1].

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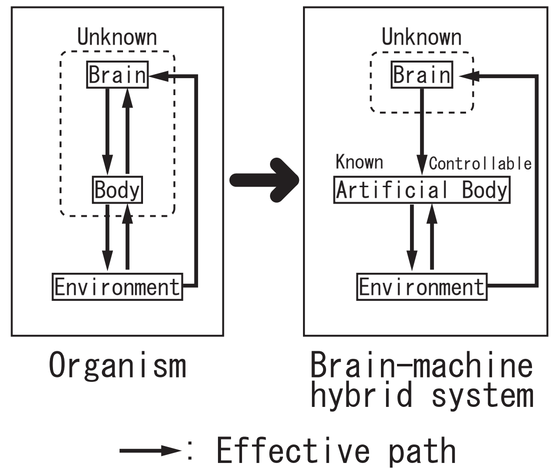


Fig. 1. Concept of a brain-machine hybrid system. The brain-machine hybrid system makes investigation of a brain possible, by replacing an organism's body with an artificial body whose specification is well-known.

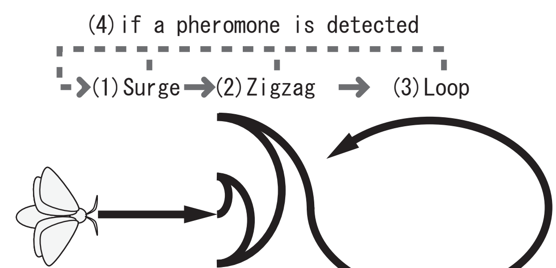


Fig. 2. Orientation behavior of male silkworm moths. In response to pheromonal stimulation the silkworm moth shows a behavior consisting of surge, zigzag turns and loop.

Fig.1 shows the concept of our BMHS. The BMHS is a kind of cyborg system in which the body of a living being is replaced by a mobile robot and its brain is used to control the robot. The artificial body is controlled by motion commands for the original body that are extracted from recorded signals in the brain. Therefore, the BMHS can help clarify the interaction loop connecting brain, body, and environment by recording the relation between the stimulation input and the action output from the brain, and by changing the characteristics of an artificial body dynamically. Consequently, it is expected that the process by which the brain adjusts to the environment can be verified.

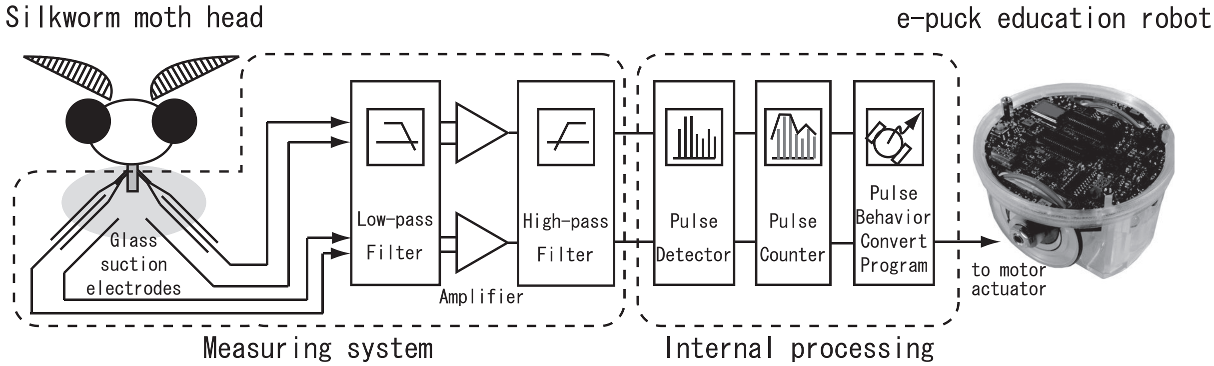


Fig. 3. Block diagram of the BMHS using a silkworm moth.

In the previous study, we showed the concept of the BMHS and built up the BMHS in computer-simulated environment[1]. In this paper, we describe more appropriate construction of the BMHS and demonstrate that the BMHS can work in real environment.

We choose a male silkworm moth as the subject, mainly because it has appropriate properties as described in the next section.

II. Characteristics of silkworm moths

The male silkworm moth, *Bombyx mori*, was chosen as the subject for three reasons.

Firstly, silkworm moths are well-known biologically and their genome[2], nervous system[3] and behavior[4] have been investigated in detail.

Secondly, the relationship between stimulus (input) and response (output) can be clearly observed. The moth does not usually move, and it only reacts to the sexual pheromone of the female. Once it detects the pheromone, the male moth performs an orientation behavior and moves towards the pheromone source, the female.

The orientation behavior develops stepwise as shown in Fig.2. Step (1) is “Surge”: while the moth is detecting the pheromone, it moves straight. Step (2) is “Zigzag”: when the stimulus is stopped, the moth starts a zigzag walk whose amplitude increases with time. Step (3) is “Loop”: If the moth cannot detect the pheromone after finishing the zigzag walk, it turns around. In Step (4), if the moth detects the pheromone, it repeats the steps from Surge. In this study, we divided moth behavior into four parts for convenience, however, the data of neural physiology suggested that “Zigzag” and “Loop” were generated by same neural circuits[3].

Finally, the orientation behavior offers a solution to the difficult problem known as the chemical plume tracking (CPT) problem[5][6]. Silkworm moths can solve the problem, despite the fact that their brain is small and simple, thus we expect that they might have some adaptability to environment.

In this paper, we regard the orientation to the pheromone source as CPT problem. We considered a successful replication of the orientation behavior and the ability to solve the CPT problem as an indicator for the success of the BMHS implementation.

III. The Brain-machine hybrid system

A. Overview of BMHS

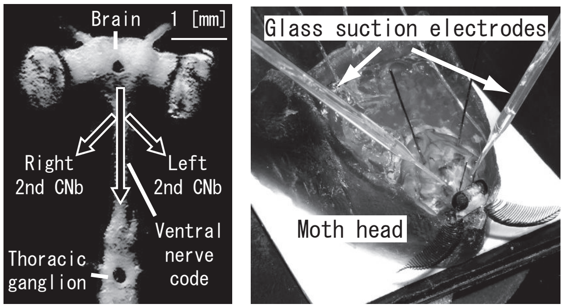
In the typical approach to investigate brain function in brain science field, the researchers have tried to understand by combining the microscopical information from genetics, animal anatomy, neuronal physiology, etc. However, it is difficult to understand the dynamic and global neural activity such as an adaptability because the information are biased to static data. Therefore, another new methods for recording dynamic activity of neurons or for analyzing of dynamic informations are explored.

Recently, the new methods to record brain activity, functional magnetic resonance imaging (fMRI), positron emission computerized-tomography (PET), electroencephalogram (EEG), implantable electrode, and so on, were developed[7], [8]. Using these methods, we were able to observe the working brain which interacted body and environment. The typical application of these technology is Brain-Computer Interface (BCI)[9].

Our proposed BMHS also is a kind of the BCI, but it has unique characteristics. That is the same identified nerves that send motion commands are recorded in all experiments. What is more, the BMHS can move freely on the experimental environment while recording neural activity and interact with the dynamically-changed environment through the artificial body.

B. Components of BMHS

The proposed BMHS has two blocks as shown in Fig.3 to investigate the mechanism in the silkworm moth brain. The left block is “Measuring system”. Our hardware implementation consists of glass suction electrodes, manipulators, noise filters and instrumentation amplifiers. The right block is “Internal processing” which was implemented as software on an e-puck education robot that was developed by EPFL[10]. To obtain the necessary grip on the substrate, the original tires were exchanged for wider ones.



(a) Central nervous system of the silkworm moth.

(b) Recording preparation. Command signals generated in the brain are recorded from left and right cervical nerves (CNbs) using glass suction electrodes.

Fig. 4. Method to record neural signal.

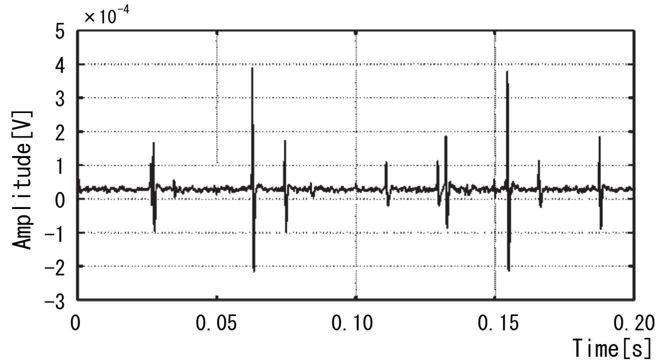


Fig. 5. Neural activities recorded from 2^{nd} CNb. Five different neural activities are recorded with different amplitudes.

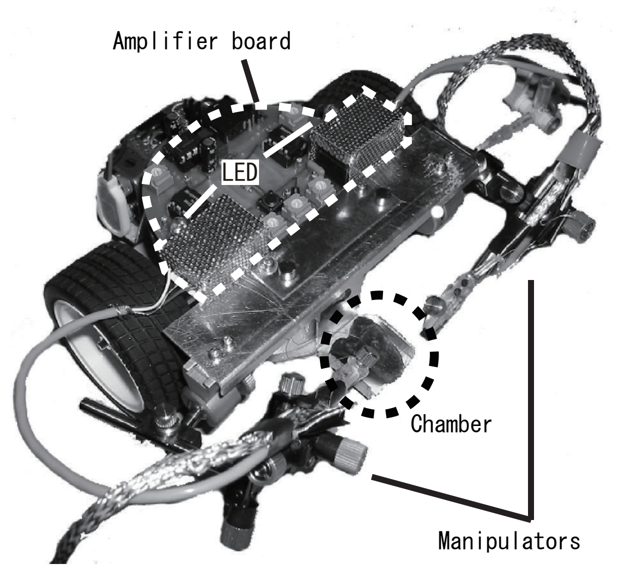


Fig. 6. Complete view of the brain-machine hybrid system(BMHS). The BMHS has two micro manipulators to hold glass suction electrodes, a micro amplifier and LED makers.

C. Measuring system on the BMHS

The nervous system of the male silkworm moth is shown in Fig.4(a). Behavioral commands are generated in the brain, and they pass through the ventral nerve cord to the thoracic ganglion, from where they are transmitted to several nerves[11]. The commands are translated into behaviors in the thoracic ganglion. We recorded the transmitted commands as neural signals from neck motor neuron, the second cervical nerve ventral (2^{nd} CNb) branches, because the neuron transmits just a copy of the command signal which is generated in the brain and is easy to connect an electrode. Furthermore, the command signal does not go through the thoracic ganglion. It is a behavior command for neck sidewise movement. Therefore, the commands are easily identified from the signals since they are assumed to appear as firing rate.

To record the neural signals from 2^{nd} CNb, we used glass suction electrodes (Fig.4(b)). The signals were amplified by instrumentation amplifiers on the mobile robot. The robot counted the spikes in the signals, and adjusted the velocity of its motors according to the firing rate.

The measuring system for recording neural signals from 2^{nd} CNb is an important component of the BMHS. The system was composed of the following subunits:

- Glass suction electrodes for recording 2^{nd} CNbs
- Amplifiers for gaining the signal from 2^{nd} CNb

Moths were prepared as follows. After cooling (4 °C, approximately 30 minutes) in order to achieve anesthesia, the abdomen, all legs, dorsal part of the thorax, and wings of the moth were removed. The male was mounted ventral-side-up on a wax chamber. The ventral part of the neck was opened to expose the cervical nerves and the ventral nerve cord that consists of two fused connectives. In addition, the moth was set upside down because of the limitation of dissection manner, however, it had been observed that there was no effect on the behavior.

Several kinds of electrodes are available to record neural signals. For example, there are hook electrodes, glass suction electrodes, and so on. We adopted glass suction electrodes, because they provide stable recordings resistant to vibration. The electrodes represent a high source impedance in the megaohm range requiring impedance conversion at the input stage of the instrumentation amplifier, which allows differential recording to reduce interference.

Our amplifier provides enough gain to make full use of the analog-digital conversion range of the microcontroller employed.

The amplifier had an input impedance of 100 (MΩ), a variable gain from minimum 0 to maximum 80 (dB), a bandwidth from 150 (Hz) to 3.2 (kHz).

A typical recording of a neural signal is shown in Fig.5. The signal contains spikes of several different amplitudes, which represents different motor units running in the same nerve. Spike rates of these units are assumed to encode the command information for the target muscles.

2^{nd} CNb contains 5 neurons, however, we did not perform spike-sorting in the present scope. Here, we use the firing rate of all spikes in the nerve in 0.1s windows as a command information.

D. Implementation of BMHS

The BMHS designed in this study is shown in Fig.6. The dimension of the BMHS was 110 (mm) (L) × 110 (mm) (W) × 50 (mm) (H). The moth head was fixed on the chamber. The glass suction electrodes were held by the micromanipulators. The signals were amplified by noise-protected amplifier on a printed circuit board and sent to a MPU of the mobile robot. To track the trajectory of the BMHS, we mounted LEDs on it as position detection makers. In an experiment, we took the movie by the camera that is set on the upper position and then constructed the system's trajectory by image processing.

IV. Signal processing from neural signal to behavior

A. Relationship between neural signals and motion of moth

As stated above, the neural signal from 2^{nd} CNb contains motion information. However, the relationship between motion of silkworm moth and neural signals is not trivial. Therefore, we derived a transformation from the signal of neck motor neurons to the behavior comprising three steps.

First, to decode the neural signal, we conducted a preparatory experiment in which the relationship between motion of neck and turning behavior was recorded and derived the relationship between the neural signal and the motion of moth. After that, using simple two-wheeled vehicle model to represent the body of moth, the relationship between velocity of wheel and motion of the model was calculated. Combining these results, we finally constructed the transformation law from the neural signal of silkworm moth to the motion of the vehicle.

At first, we regarded the silkworm moth as simple two-link model which was shown in Fig.7. The neck angle and the body axis were indicated as ϕ and θ respectively. In the preliminary experiments, a tethered moth was stimulated with puff of pheromone and the body axis and the neck angle were recorded. In such experiments, it seems that the change of neck angle synchronizes with the angular velocity of the body axis[12]. A typical result is shown in Fig.8, where the correspondence between ϕ and $\dot{\theta}$ of each section (a)–(c) was observed. From these results, we regard the following relationship:

$$\dot{\theta} \propto \phi. \tag{1}$$

2^{nd} CNb is a neck motor nerve, its signal represents the command to activate neck muscles for bending the neck. In this paper, we assumed that the neck angle ϕ was proportional to the number of neural spikes n (n_l is left, n_r is right respectively) in constant period ΔT:

$$\phi \propto n_l - n_r. \tag{2}$$

From (1) and (2), we deduced the following equation:

$$\dot{\theta} \propto n_l - n_r. \tag{3}$$

Next, we derived rules governing the walking velocity v. A male silkworm moth rarely moves in the absence of pheromone stimulation. On the other hand, while the

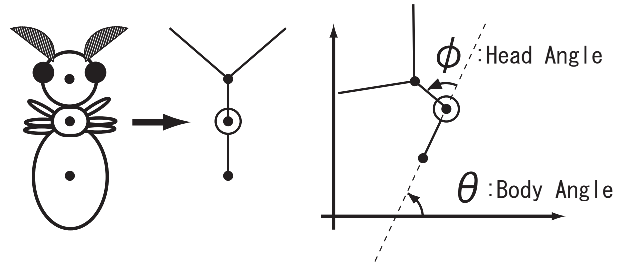


Fig. 7. Body axis and head axis. The moth abstruct

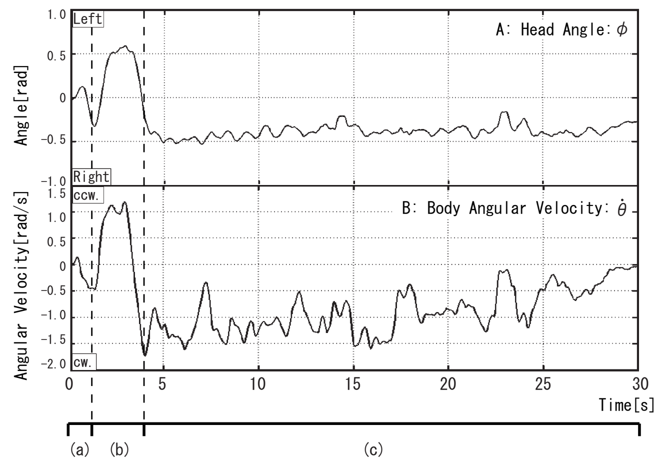


Fig. 8. Correspondence between head angle (A) and angle of body axis (B). The moth is stimulated with pheromone at 0 (s)].

pheromone stimuli are being given at over 2 (Hz), the moth walks straight[13]. Similarly, 2^{nd} CNbs fire at low rate without stimulus and they also fire at high rate under the high frequency stimulation. Therefore, in this paper, we assumed the velocity v was proportional to 2^{nd} CNb activity.

$$v \propto n_l + n_r. \tag{4}$$

As a result, we obtained the relationship between neural signals and moth behavior. The motion of silkworm moth follows (3) and (4), and it seems not to sideslip. Therefore we regarded the moth as nonholonomic system which is shown in Fig.9.

B. Motion of artificial body

In this section, we considered the motion of artificial body which replaced the body of moth. In this paper, we adopt simple two-wheeled vehicle model, shown in Fig.9, as the body of the BMHS. The width of the BMHS is $2R$ and the center of moving is O. Its velocity and angular velocity are V_O and $\dot{\theta}_O$ respectively. V_r and V_l represents the right and the left velocity of the BMHS.

The angular velocity of center O is derived from the velocity V_l and V_r:

$$\dot{\theta_O} = \frac{V_l - V_r}{2R}. \tag{5}$$

The velocity is calculated in the same manner:

$$V_O = \frac{V_l + V_r}{2}. \tag{6}$$

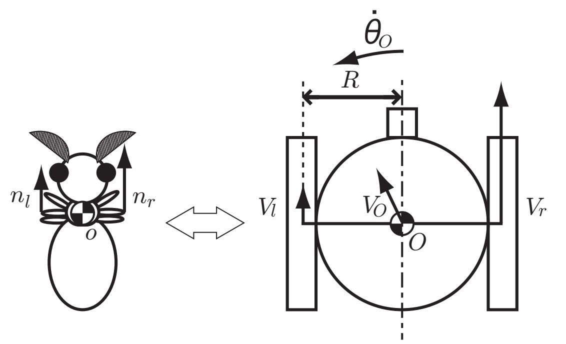


Fig. 9. Moth behavior model and two-wheeled vehicle model.

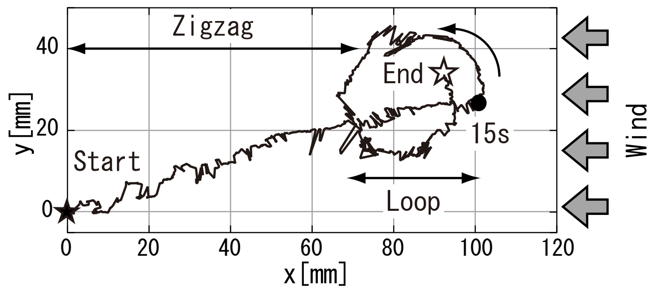


Fig. 10. Trajectory of the BMHS in response to a pulsed pheromonal stimulation. The black star indicates the start point and the white star indicates the end point. The black dot indicates the position of the BMHS at 15 (s) where the BMHS changed its behavior.

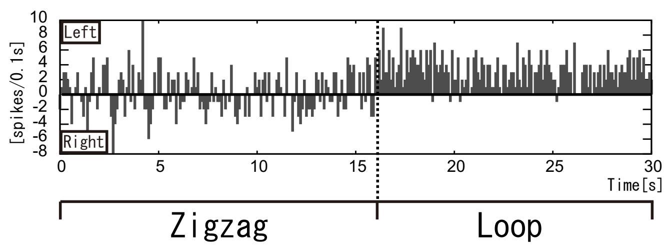


Fig. 11. Difference between histograms of firing rate of left 2^{nd} CNb and right 2^{nd} CNb. The area in which the value of histogram is positive means that the BMHS turn left.

Finally, to correspond $\dot{\theta}$ and v with $\dot{\theta_O}$ and V_O respectively, the transformation law from spikes to the behavior are led from (3), (4), (5), (6):

$$V_L = \alpha(n_l + n_r) + \beta R(n_l - n_r), \quad (7)$$

$$V_R = \alpha(n_l + n_r) - \beta R(n_l - n_r), \quad (8)$$

where α and β are proportional constants which are calculated to satisfy (5) and (6).

Using these transformation laws, the BMHS was able to behave as a silkworm moth.

V. Experiments of the BMHS

A. Experiment settings

As the consequence of the combination of the anatomical preparation, the artificial body and the transformation law, the BMHS was constructed.

In the experiment of the BMHS, we used a wind tunnel to simulate realistic pheromone stimulation conditions. Wind speed was set to approximately 0.7 (m/s). A video camera was installed on the ceiling to record the motion of the BMHS. At the same time, the signals from 2^{nd} CNbs were recorded by a PC. Notice that, the PC was used to record the signals only and never sent back any signals to the BMHS during experiments.

We selected moths that exhibited correct behavior reacting to pheromone stimuli. After the dissection, we also checked neural activities of neurons in 2^{nd} CNbs. If we cannot record more than 4 different activities of the neurons in an individual, we did not use it.

B. Sequential movement

We set the BMHS in the wind tunnel. We gave a puff stimulus to the moth on the BMHS, and then the BMHS started to move.

The trajectory of the first trial is indicated in Fig. 10. The initial position of the BMHS was (0,0). The BMHS run towards windward where it initially set up direction . The BMHS moved with turn zigzagging in the Zigzag interval (Start–15(s)); it corresponds to “Zigzag” in Fig.2. And then the BMHS turns around (15(s)–End); it corresponds to “Loop”.

The difference between histograms of firing rate of left 2^{nd} CNb and right 2^{nd} CNb during the experiments is shown in Fig.11. The difference can be divided into Zigzag (0–16(s)) and Loop (16–30(s)) intervals. The angular velocity of BMHS is shown in Fig.12. It also can be divided into Zigzag sequence and Loop sequence.

This result showed that the BMHS was able to react to the pheromone and could show a behavior similar to that of an intact male silkworm moth.

Finally, we examined whether the BMHS can solve the CPT problem.

C. Pheromone orientation

The BMHS was tested in a wind tunnel with a pheromone source. In this experiment, we did two trials using the same silkworm moth. At first, we conducted experiment to get trajectory of silkworm moth in normal condition. Next, we dissected the moth and built up the BMHS. Then we carried out the second trial to get trajectory of the BMHS. Finally, we compared the results.

We did first trial to record the trajectories of silkworm moths. An example is shown represented by the thin line in Fig.13. Using these data, we determined α and β in (7) and (8). Afterwards, the second experiment was repeated with the BMHS incorporating the same individual moth.

Fig.13 shows trajectories of the moth and the BMHS. Both moth and BMHS were set at the black star (0,0) And the pheromone source was set at the black triangle (600,0). The pheromone was spread in the wind tunnel. The goal area is defined as the circle with a radius of 100 (mm) from the pheromone source. The trial is considered to be completed (stopping condition) when the BMHS reaches the goal area.

From the start point, the BMHS moved straight and

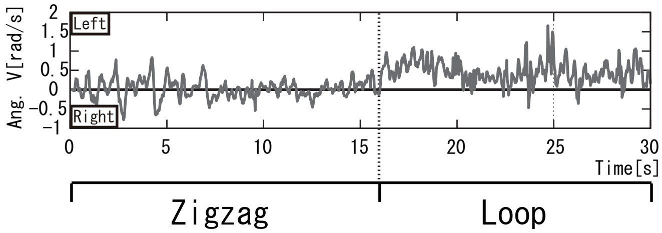


Fig. 12. Angular velocity of BMHS. The area with positive value means that the BMHS turns counterclockwise. Same data as Fig. 11. The interval from 0(s) to 15(s) indicates that the BMHS moved zigzagging and the interval from 15(s) indicates that the BMHS turned around.

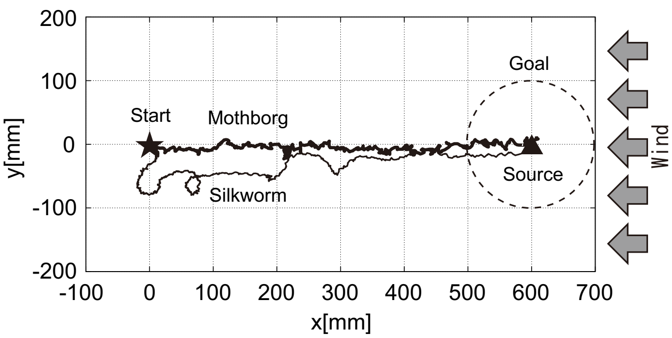


Fig. 13. Trajectory of the moth and the BMHS were represented in gray line and black line respectively. The black star indicates the start point. The black triangle represents the location of the pheromone source. A current of air was blown from right side to left side and its velocity was approximately 0.7 (m/s).

zigzagged in the windward direction. It continued to move and then arrived at the goal area. The BMHS traced almost the same as the path of the moth. The BMHS traced a small zigzag loop when moving from the start point to end point. Because the BMHS was in the windward direction relative to the pheromone source, it might had been continuously stimulated by the pheromone.

Table I shows the time until the orientation and the average angular velocities. The orientation time of the BMHS is similar to the time of the moth. And the angular velocity of the BMHS is also similar to the one of the moth. This shows the signal transformation worked as expected.

VI. Conclusion and Future Work

We developed a BMHS that could solve the CPT problem and replicate the motion of a male silkworm moth. We confirmed the BMHS have the ability to reproduce the orientation behavior of silkworm moths. Using comparative experiments with moths and BMHSs with the same moths, we demonstrated that the BMHS had the same capabilites as the moth as no significant differences in behavior were detected. Biologically speaking, we showed that the brain of moth was able to control the robot body and move in experimental environment. While experiments, we confirmed that neural signals through the BMHS were able to be recorded. We thought that the orientation of the BMHS might be the evidence that the moth's brain adapted to the artificial body.

We are planning to add another amplifier to the BMHS in order to record the signal from the antenna. In the near future, we will investigate the signal processing in the brain by using the signal from the antenna (INPUT) and the 2^{nd} CNb (OUTPUT).

TABLE I

The orientation time and the average velocity of the experiment.

	Silkworm moth	BMHS
Orientation time (s)	32	28
Average velocity (mm/s)	33.7	38.7

Acknowledgement

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