Property Investigation of Chemical Plume Tracing Algorithm in an Insect Using Bio-machine Hybrid System

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Abstract. In this study, we investigated an aspect of the chemical plume tracing behavior of an insect by using a bio-machine hybrid system. We implemented an experimental system by which an insect brain was connected to a robot body. We observed th neural responses to external disturbances and transitions at changes in the motor gain of the robot body. Based on the results of the experiments, we identified a simple control model for the angular velocity of the behavior. We subsequently investigated the effect of the rotational velocity by using information entropy in computer simulations.

Keywords: chemical plume tracing, bio-machine hybrid system, silkworm moth.

1 Introduction

In this study, we investigated an aspect of an insect's behavior locating a chemical source. In air, chemicals form several plumes rather than a smooth gradient. Locating a chemical source by following these plumes is known as the chemical plume tracing (CPT) problem [1][2]. CPT is potentially important for artificial systems because it can be applied to the location of the source of pollution, finding people trapped under debris after large earthquakes, etc. Because the dynamics of chemicals in the atmosphere are quite complex, we found it beneficial to investigate the adaptive behaviors exhibited by an animal to solve the CPT problem.

Animals effectively use CPT for foraging, mating, localizing, etc. In contrast to robots, most animals, including insects, have the ability to solve CPT problems. In this study, we investigated the CPT performance of insects by using an insect brain machine-interface system, called a bio-machine hybrid system. We then considered the effects of motion parameters by using computer simulations and information entropy.

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2 Instruments and Methods

2.1 Silkworm Moth *Bombyx mori*

In this study, we employed an adult male silkworm moth, Bombyx mori (Fig. 1). Silkworm moths have more than 5,000 years of history as domestic insects, and their genome [3], nervous system [4], and behaviors [5] have been thoroughly investigated.

An adult silkworm moth does not drink, eat, or make any voluntary movements. The only thing it does is attempt to locate a female for mating using the pheromones that she releases. Thus, the correspondence between input stimuli and exhibited actions is very clear. This characteristic of the silkworm moth makes it a suitable subject for CPT research.

Fig. 1. Adult male silkworm moth *Bombyx mori*

A silkworm moth has a set of actions, called programmed behavior, which it uses to locate a female [5]. As shown in Fig. 2, it walks straight when it receives a stimulus. This action is called *surge*. It then changes its walking direction from left to right as if it is looking around (*zigzag*). Finally, it continues turning for a period of time (*loop*). If the moth receives another stimulus during this programmed behavior, it restarts the sequence from *surge*.

Kanzaki et al. reported the typical parameters of this programmed behavior [6]. A moth does not move until it receives pheromone stimuli. During *surge*, it walks for 0.5 [s] at 26 [mm/s]. A *zigzag* procedure typiaclly contains three turns, whose durations are 1.2 [s], 1.9 [s], and 2.1 [s]. The angular velocity during *zigzag* or *loop* is 1.0 [rad/s].

The research says that a moth arranges its programmed behavior adaptively based on environmental conditions. The CPT behavior is understood qualitatively based on previous research, but how the moth arranges its actions according to its environment remains unclear. Therefore, we built a system to observe a moth's behaviors and neural activities simultaneously.

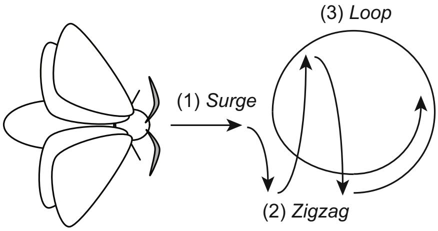


Fig. 2. Programmed behavior of silkworm moth

2.2 Bio-machine Hybrid System

We developed an experimental system called a bio-machine hybrid system [7]-[9], in which a living brain controls a robot body. This system can be categorized as a closed-loop experimental platform (i.e. [10][11]).

Fig. 3 illustrates the implemented hybrid system. At the front of the body, the system is equipped with a chamber where the head of a living moth is set in wax. Through micro glass electrodes, neural signals containing motion commands are sent to a micro controller on the robotic body and are translated into wheel movements. Using this system, we can observe the neural activities corresponding to the behaviors on line.

Although it has wings, a silkworm moth cannot fly. According to the observed trajectories, to simplify the problem, we applied the kinematic model of a two-wheeled mobile robot to that of a moth. In other words, we used a two-wheeled mobile robot as the body of the experimental system. By observing the neural signals of the neck motor neurons at the second cervical nerve b (2nd CNb)[9][12], we counted the firing ratio of neurons and translated them into motion commands for the left and right electric motors. Note that the 2nd CNb consists of 5 motor neurons and innervates the neck muscles, which contract during horizontal side-wise head movement[13][14]. Based on the previous works [9],[12]-[14], we measured all of the activities of these 5 neurons. We had already obtained some results for locating a pheromone source in a simplified environment by using the experimental system [15][16].

2.3 Preparation of Moths

Moths were prepared as follows. After cooling at 4° C for 30 [min] to achieve anesthesia, we removed the abdomen, all of the legs, the dorsal part of the thorax, and the wings. Owing to the operation method, the moth was mounted ventral-side-up in a chamber of the robotic body. The ventral part of the neck was opened to expose the cervical nerves and ventral nerve cords. We employed two micro glass electrodes to record and observe the neural activities of the 2nd CNb on both the left and right sides. For this purpose, we filled the chamber with normal saline and covered it with wax.

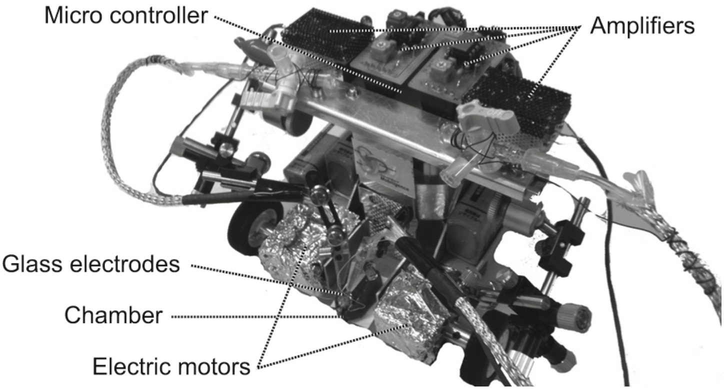


Fig. 3. Proposed bio-machine hybrid system

3 Experiments by Using Bio-machine Hybrid System

We conducted some experiments in order to investigate the properties of the control system in a brain of a moth with the robotic body.

First, we observed the compensations against external disturbances. We introduced unexpected motions to the hybrid system, and then observed the neural responses from the left and right 2nd CNb neurons. We tested the sensitivity to two types of disturbances, rotational and translational (Fig. 4). We gave the robot forced movements, yaw rotations and forward-and-backward translations, and recorded the neural responses. In these experiments, we observed clear responses in the 2nd CNb to the rotational disturbances, but not to the translational ones. We also found that the neural responses were proportional to the angular velocity of the imposed movement. Therefore, in this study, we focused on the rotational disturbances and the identification of a control system for the angular velocity in a moth.

Fig. 5(a) shows a possible block diagram for the hybrid system. In our current system, we could not measure the intention of a moth, which is expressed as r in the figure. Thus, we only focused on the exhibited angular velocity. We considered a transfer function from the external noise to the output. Therefore, we simplified the diagram, as shown in Fig. 5(b), and identified the feedback transfer function, which is expressed as PCS in the figure.

In order to simplify the problem, we employed a linear output error model (1), where q is the shift operator.

$$y(k) = \frac{b_1}{1 + f_1 q^{-1} + f_2 q^{-2}} d(k) + w(k) \tag{1}$$

For identification, we assumed that w is white noise. We identified the parameters for the model in two cases: the robot body (P) with normal motor gain and

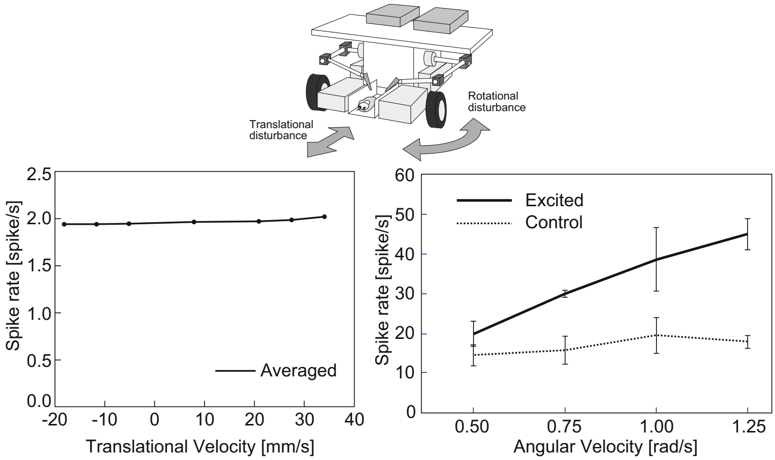
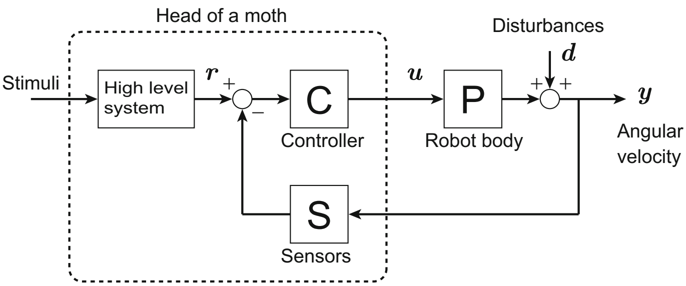
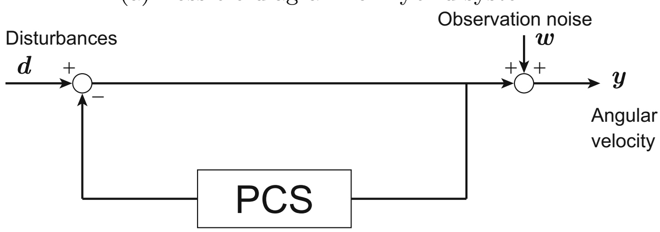


Fig. 4. Neural response to disturbances



(a) Possible diagram for hybrid system.



(b) Simplified diagram under $r = 0$.

Fig. 5. System expressions for identification

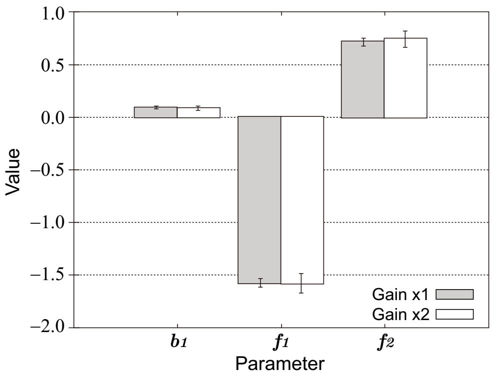


Fig. 6. Results of identification

body with twice the normal gain. The results shown in Fig. 6 indicate that the parameters were the same for the two cases. From these results, we considered that the parameter values in a natural moth were important.

We then conducted additional experiments. During the CPT movements, we changed the gains to rotate the electric motors on the robot body. We prepared a wind tunnel, as illustrated in Fig. 7. The bio-machine hybrid system was set 600 [mm] away from the nozzle of a pheromone injector.

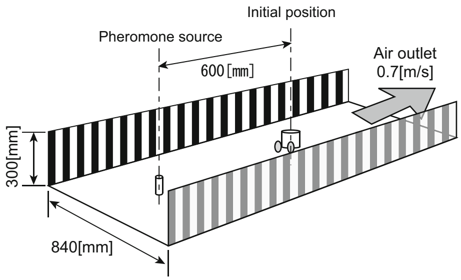


Fig. 7. Wind tunnel for experiments

At the beginning of the experiment, the normal gain was used for the hybrid system. After 10 [s] of CPT movements, we instantly doubled the motor gain for another 10 [s]. We then restored the original motor gain for an additional 10 [s].

Although we changed the motor gain, the hybrid system worked well, as if it adapted to the changes in motor gain, and arrived at its goal position. As shown in Fig. 8, the moth arranged the firing ratio of the neurons. According to the results, we considered that a moth regulates its motor responses. We then attempted to evaluate the effectiveness of the value of rotational velocity in the modeled behavior [6] by using a simplified artificial model.

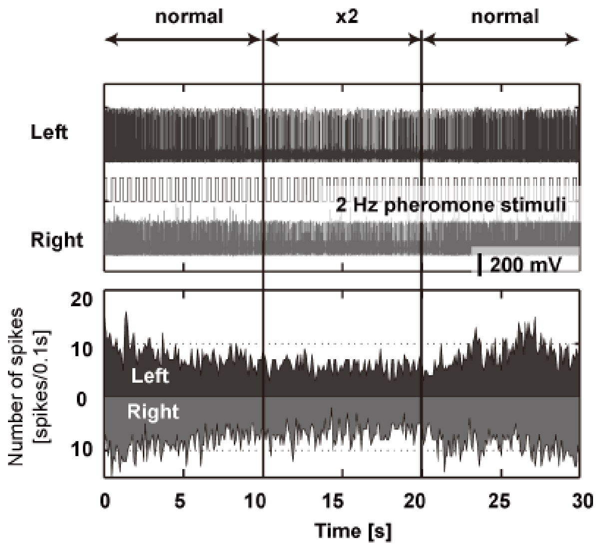


Fig. 8. Adaptation of neural activities to changed motor gain

4 Evaluation of Rotational Velocity

4.1 Information Entropy

According to the experiments, we hypothesized that the values of the rotational velocity in the behavior of a moth were adjusted appropriately. In [6], the rotational velocity of a natural moth was reported to be approximately 1.0 [rad/s]. Thus, we attempted to evaluate the effectiveness of the rotational velocity in CPT.

To validate what was obtained from previous experiments, the entropy of the system was studied. If the behavior of a silkworm moth was correct, the entropy had to reflect the statements made in [17] and [18]: its value had to decrease as the moth searched for the location of the pheromone source. The definition of entropy S for a probability distribution $P(r_j)$ is as follows:

$$S = \sum_j P(r_j) \ln P(r_j) \tag{2}$$

where r_j is the pheromone source location.

Formula 2 intuitively shows that the information entropy is large when the probability density distribution spreads uniformly: in fact, the maximum value of S is $\log N$, corresponding to the situation in which the same probability characterizes the whole field. This means that the entropy has a large value when little information is known about the goal position, whereas the entropy is small when the approximate goal position is known. Mathematically, $S = 0$ if and only if there is no uncertainty in the field, i.e., the location r_j of the source is known. In this case $P(r_j) = 1$ and $P(r_i \neq r_j) = 0$ for all other events.

In order to study the rate of reduction of the entropy in the estimated probability distribution during CPT, a Java simulator was developed. This system used the same physical distribution model used in [17], because we did not have a concrete model of the chemical plumes in our wind tunnel. It was composed of a moth, initially situated 500 [mm] away the pheromone source, and a pheromone source located at position r_o $(0, 0)$ (Fig. 9).

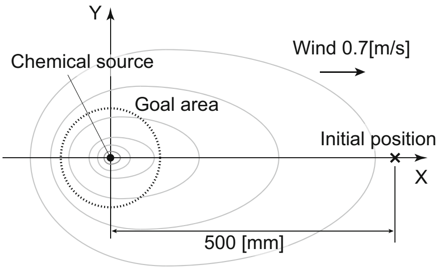


Fig. 9. Overview of the simulation field

The source emits detectable particles at a rate $R = 1.0$ [mm^2/s], and every stimulus has a finite lifetime $\tau = 150$ [ms], is propagated with an isotropic effective diffusivity $D = 1.0$ [mm^2/s], and is advected by a wind current characterized by a speed of approximately 0.7 [mm/s]. The wind has been taken to blow in the negative X-direction. The moth reaches the source if it reaches a goal area defined as a circle with a radius of 100 [mm] from the pheromone source. In this kind of system, the agent was modeled as a spherical object with a small linear size $a = 0.01$ [mm]. It should be rememberd that the system has the purpose of simulating the bio-machine hybrid system, so the agent represents the system and not the real moth. However, moving into such media the agent will experience a series of encounters at rate $R(r|r_0)$:

$$R(r|r_0) = \frac{R}{\ln \frac{\lambda}{a}} e^{\frac{(x_0 - x)V}{2D}} K_0(\frac{|r - r_0|}{\lambda}), \tag{3}$$

where

$$\lambda = \sqrt{\frac{D\tau}{1 + \frac{V^2\tau}{4D}}} \tag{4}$$

and K_0 is the modified Bessel function of order zero. In detail, $x_0 - x$ corresponds to the length along which the wind blows, and $r - r_0$ is the distance that separates the current location of the agent from the source.

The agent is asked to perform the motion described at the beginning of this section, and the rate $R(r|r_0)$ allows the simulator to compute the position reached by the agent at each moment. An array of positions input to a

Matlab system makes it possible to evaluate the trajectories and calculate the entropy of the system at every point of the map. At every point, the system will calculate the probability distribution and, as a consequence, the entropy of the system. At the beginning, the estimated probability of the location of a chemical source will be distributed uniformly over the entire space; thus, all of the points will have equal probabilities. Then, this distribution will vary over time with the same trend as a Gaussian function with expected value μ and variance σ, formulated according to the distance from the pheromone source:

$$P(r|r_0) = \frac{\frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r-\mu)^2}{2\sigma^2}} P(r|r_0)}{\sum_i \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(r_i-\mu)^2}{2\sigma^2}} P(r_i|r_0)} \tag{5}$$

4.2 CPT Performance

We applied rotational velocities of 0.5 [rad/s], 1.0 [rad/s], 2.0 [rad/s], 3.0 [rad/s], 4.0 [rad/s], and 5.0 [rad/s] to the simulations. We conducted 20 trials for each velocity.

These trials included a search time upper bound equal to 300 [s]. It has been shown experimentally that this leads to an optimal tradeoff between exploration and exploitation. In fact, on average, in 70 % of the cases, the moth reaches the goal area within this time.

Using an upper bound of 600 [s] leads to reaching the source in all 20 samples, but an increase in the bound is not proportional to the improvement obtained: doubling the time results in an improvement of only +30 %. Likewise, decreasing the bound results in drastic reduction in performance: only 40% of the agents reach the source if the upper bound is decreased by 60 [s].

The transition of the information entropy observed is shown in Fig. 10. Figure 11 also shows the ratio to reach the goal area and the average search time.

The values plotted in Fig. 10 are the averages calculated after 20 tests, and the different lines correspond to different angular velocities. The entropy decreases over time as the agent gets closer to the source. It has a maximum value when the agent is located at the farthest position and a minimum value when the moth reaches the goal.

The minimum search time, as shown in Fig. 11, is that corresponding to an angular velocity of 0.5 [rad/s]. However, in that case, the success ratio was quite low. In Fig. 10, we can find that the moth agent did not survey the environment because the information entropy in that case decreased slowly. Thus, if the moth agent reached the goal area by chance, it spent a shorter amount of time. In the case of 1.0, the moth agent performed well, with a high success ratio and short searching time (Fig. 11). In this case, the information entropy shown in Fig. 10 decreased quickly and achieved a low value. We consider that the moth agent in this case did well both in surveying the environment and reaching the pheromone source. If a moth can move at 4.0 [rad/s] or more, it will achieve the highest success ratio, but it needs a longer time than that of other cases.

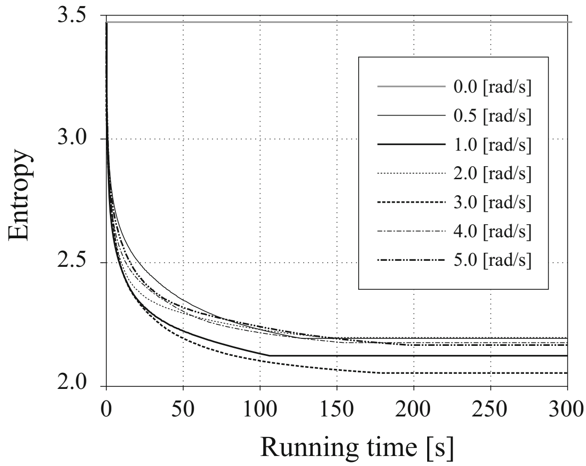


Fig. 10. Information entropy during CPT behavior with different values of rotational velocity

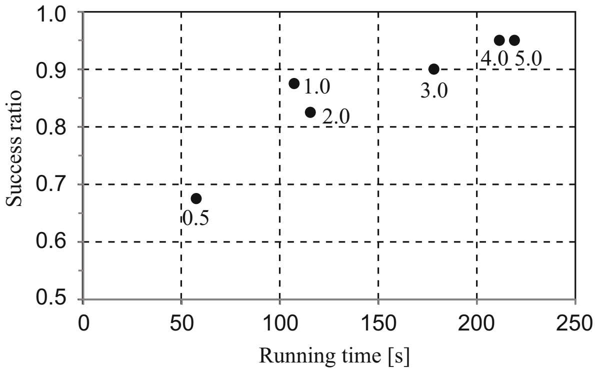


Fig. 11. Success ratio and search time. The values indicate the corresponding rotational velocity.

The best balance among the success ratio and searching time seemed to be 1.0 [rad/s], confirming the statement made by Kanzaki et al [6].

From the perspective of information entropy, the behavior of a silkworm moth, including the parameter settings obtained by our experimental system, was well adapted for achieving CPT.

5 Conclusions

In this study, we investigated the chemical plume tracing (CPT) behavior of an insect by using a bio-machine hybrid system. We implemented an experimental system by which an insect brain was connected to a robotic body. We observed the neural responses to external disturbances and adaptation to changes in the motor gain of the robotic body. Based on the results of experiments, we carried out the simple identification of a control model for the angular velocity of the behavior. We then investigated the effect of the rotational velocity by using the information entropy in computer simulations.

Based on the results of the experiments, we hypothesized that the values of the parameters in the programmed behavior of a moth were regulated as the best values. We then attempted to evaluate the effectiveness of the parameters by using computer simulations with a simple behavior model of the bio-machine hybrid system. From the perspective of information entropy, the behavior of a silkworm moth including the parameter settings obtained by our experimental system was well adapted for achieving CPT.

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