Modeling of the constant-current stimuli response of a bio-robot for long-term motion control

Jie Zhou, Yuan Fang, Yang Chen, Yao Li*, Bing Li, senior Member, IEEE

Abstract— **Bio-robots continue to receive attention because of their small size and low power consumption. Unfortunately, it currently faces two major obstacles before practical application. The first is the habituation issue, insects are difficult to be effectively controlled for a long time by electrical stimuli signals. The other one is the lack of model for motion control. In this research, we established a stimuli-response model for cockroach bio-robot based on long time current. A more convenient optic lobe implantation method has been proposed, which has lower attenuation and better stimuli effect. Constant electrical stimuli also significantly increased the number of effective controls for crawling. A cockroach bio-robot stimuli distance response model was established and validated with experiment data. Five parameters were including in this model, namely sex, length, weight, current amplitude and equivalent stiumated-number. This model can predict the movement distance of biological robots well.**

I. INTRODUCTION

Bio-robot is a kind of robot that combines the insect and artificial devices. Compared with micro-robots made up of electromechanical systems [1], bio-robots only need simple electrode implantation and application of electrical stimuli signals. For example, the locust [2], the beetle [3]–[5] and the jellyfish [6], can be controlled by implanting electrodes into muscle. Relies on precise contraction of muscles to accomplish localized movement control of the body. The crab [7] and the cockroach [8] were capable of movement under human command based on nerve electrical stimuli. After being stimulated, the animal would make a stress reaction and complete the movement of turning and advancing. Therefore, neural electrical stimuli is more suitable for controlling bio-robots that use the entire body as a mobile platform.

There are currently three kinds of neural interface for cockroach bio-robot. The most common interface is antennae. The cockroach's antennae is connected to electrodes by method of antennae-excision [9] or non-surgical [10]. The other one is cerci, as the cerci is also an acute sensory organ of the cockroach [11]. The third is trunk ganglion, which is usually used for forward control and in conjunction with other interfaces [10].

The habituation issue is a major obstacle for bio-robots to be put into practical applications. It refers to that the insect's (like cockroach) response will weaken and disappear under repetitive stimuli. That means bio-robot's effective control can only be sustained for a short period of time. To mitigate the effects of cockroach bio-robot's habituation, Ma [12] proposed the method of alternating antennae-to-cerci. Li [13] proposed a new algorithm through dynamically adjusting the voltage amplitude of stimuli. But they are all improvements based on tradtional single-phase voltage. Neither of them replaced single-phase voltage signal with better electrical signal. In terms of the capacity of long-lasting stimuli, it has long been concluded in the field of functional electrical stimuli that bidirectional electrical signals are superior to unidirectional electrical signals [14], [15], constant-current signals are superior to constant voltage signals [16], [17]. However, due to the limitations in the size and performance of backpacks, not just Ma and Li, almost all current studies use single-phase voltage as stimuli signal [18], [19]. Bio-robot need electronic backpacks capable of outputting bidirectional constant-current.

The lacking of basic model is another large constraint for cockroach bio-robot. Almost all the studies related to cockroach model are the explorations of cockroach biology habits [20], [21] or the algorithms proposed to imitate the behaviour of cockroach populations [22], [23]. They are both conducted on cockroaches in natural state. Weight-bearing and electrical stimuli—the two most important factors of bio-robot are not taken into account. It's important to understand that the cockroach bio-robots and the cockroaches in natural state are two completely different concepts. As a kind of unconventional control object, cockroach bio-robot's basic movement process —stimulated-motion response hasn't been quantitatively described by anyone.

In this research, we proposed a low-habitation stimuli method and modeled the stimuli response with the consideration of attenuation. The stimuli method was implemented by using constant-current stimuli and optic lobe implantation. Meanwhile, cockroaches were tested in response to constant-current stimuli and compared with data based on voltage sig-

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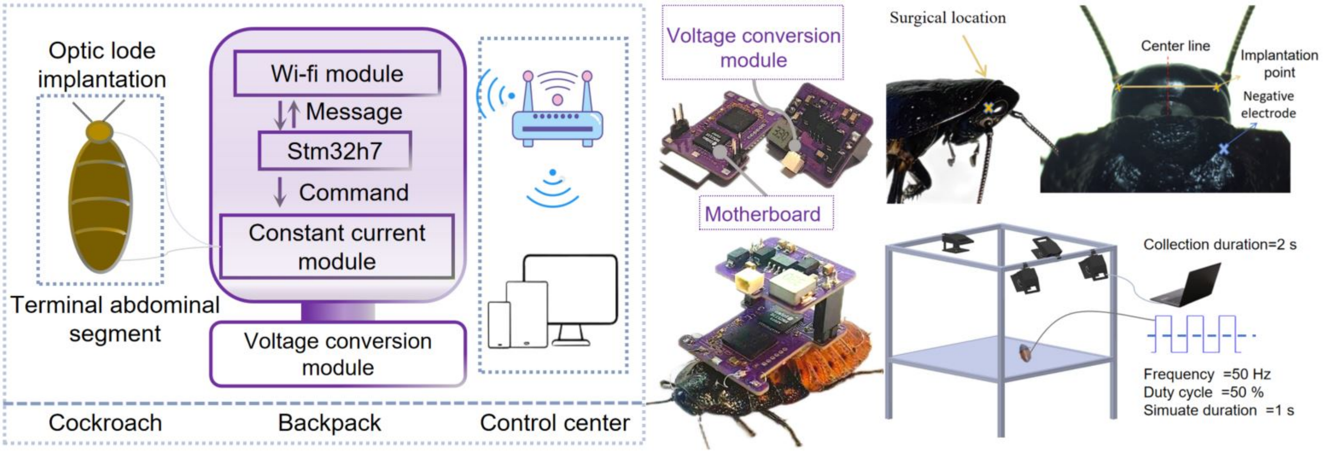
Jie Zhou, Yuan Fang and Yang Chen are with Guangdong Provincial Key Laboratory of Intelligent Morphing Mechanisms and Adaptive Robotics, with Key University Laboratory of Mechanism & Machine Theory and Intelligent Unmanned Systems of Guangdong, and with School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen, 518055, China.

Yao Li is with Guangdong Provincial Key Laboratory of Intelligent Morphing Mechanisms and Adaptive Robotics, with Key University Laboratory of Mechanism & Machine Theory and Intelligent Unmanned Systems of Guangdong, and with School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen, 518055, China. (e@mail: liyao2018@hit.edu.cn).

Bing Li is with with Guangdong Provincial Key Laboratory of Intelligent Morphing Mechanisms and Adaptive Robotics, with Key University Laboratory of Mechanism & Machine Theory and Intelligent Unmanned Systems of Guangdong, and with School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen, 518055, China. (e@mail: libing.sgs@hit.edu.cn)



(a) (b)

Fig. 1. Backpack and experiment methods. (a) Frame diagram of constant-current stimuli backpack and photographs of the real backpack. (b) The postion of optic lobe implantation and motion acquisition system.

nals. Last, based on the above work, we filled the theoretical gap and built the first continuous stimulus-motion response prediction model for cockroach bio-robot.

II. EXPERIMENT METHODS

A. Optic lobe implantation

The use of cockroach was permitted by the Animal Ethical and Welfare Committee(IACUC-2020026). The cockroach, *Gromphadorhina portentosa*, were bought from local pet stores and selected for the experiments. They were kept with pet feed and water once a day. The temperature of the feeding environment was 25°C and the humidity was 60%.

The cockroach was anesthetized in carbon dioxide gas for 1 minute, and then its head was fixed to the brain localizer. After the platinum electrode (76.2 µm uncoated diameter, 139.7 µm coated diameter, A-M Systems) tip insulation was removed, it was implanted directly into the bilateral optic lobes from a location near the cockroach's eyes, as shown in Fig. 1(b). The depth of electrode implantation was 2 mm. After the electrode is implanted, it was fixed with glue.

B. Motion Parameter Acquisition

The motion acquisition system is described in Fig. 1(b). Motion parameters (turning speeds, forward crawling speeds and distance) were obtained with the help of the three-dimensional (3D) motion capture system (8×Vicon V5 cameras; Oxford Metrics Ltd, Oxford, UK) cooperating with two reflective markers attached to the back of cockroaches. The acquisition frequency was set to 200 frames per second (fps). The signal required for stimuli was produced by function generator. All durations of stimuli in this work were 1 s. All durations of vicon acquisition were set to 2 s since cockroaches didn't stop moving immediately after the end of stimuli.

C. Design of Constant-current Stimuli Backpack

A backpack has been designed for constant-current stimuli. Fig. 1(a) shows the framing diagram of the electronic backpack. A voltage conversion module ensures stable power supply for the electronic backpack. With the help of a router, a Wi-Fi module is used to set up a local area network (LAN) with a host computer. An Intan (V063) chip-based constant-current module can communicate with main control chip via Serial Peripheral Interface (SPI) and apply constant-current electrical stimuli signals. This module can output both unidirectional and bidirectional currents. The adjustable range of unidirectional current is 0-2550 µA and that of bidirectional is 0-5100 µA. When the current is less than 255 µA, the minimum step of current amplitude adjustment is 1 µA; and when the current is greater than 255 µA, the minimum step changes to 10 µA. This constant-current module output current square wave signal with a maximum frequency of 1000 Hz, also, it is capable of outputting a sine wave externally by setting up an external circuit.

D. Electrical Stimuli Experiment Design

1) Experiment of Electrical Stimuli response : In angular velocity response test, single-phase rectangular voltage signal (50 Hz, Voltager=2 V, Duty cycle = 50%) and bidirectional constant-current signal (Ampliute 80-110 µA, Step = 10 µA, 50Hz) were both tested; stimuli postion included optic lobe and antennae. Cockroaches (length: 3.5 ± 0.2 cm, weight: 4 ± 0.5 g) were stimulated once every 5 s, and the results were recorded in Vicon system.

In forward crawling speed response test, the stiumli signal was bidirectional constant-current signal (Ampliute 40-160 µA, Step = 10 µA, 50 Hz); stimuli postion was terminal abdominal segment. Others were the same as angular velocity response test.

2) Experiment of modeling data acquisition : Cockroaches in test are all under 7.1 g load. Amplitude interval was 100-160 µA (step = 20 µA). Fig. 2 decribes experimental procedure. Five-second time interval was used, one stimuli was randomly performed in each time interval.

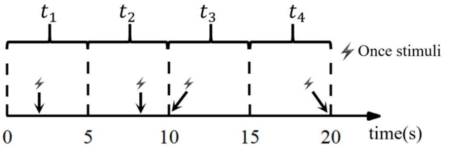


Fig. 2. Experimental procedure of modeling data acquisition. Since the vicon acquisition duration was 2 s, the minimum gap between two neighboring stimulus in this experiment was 2 s; The sitation of maximum gap was described by two adjacent stimulus in t_3, t_4. The maximum gap was 10 s, which corresponded to model preset

III. MODELING OF FORWARD CRAWLING STIMULI-DISTANCE RESPONSE

A. Theoretical Analysis

Distance is an important parameter for bio-robot due to it is suitable for low-frequency control. Cockroach bio-robot's forward crawling stimuli-distance response (hereinafter called S-D-R) is influenced by Sex, Weight (regarded as robustness), Body length (single stride distance), Current amplitude and Habituation. The Habituation is an abstract parameter related to time and NS (the number that cockroach has been stiumated). To quantify the habituation, Equivalent-NS and Window Duration(ΔT_s) was defined here.

- Equivalent-NS(EqNS): a cockroach's origin EqNS is N_0, if it received an stimuli within ΔT_s seconds, the EqNS will change to N_1; similarly if the cockroach is stimulated again within the next ΔT_s seconds, its EqNS change to N_2, and so on.
- The backspace of EqNS: assuming that a cockroach's current EqNS is N_i, m is a positive integer. If cockroach doesn't be stimuated within $m \times \Delta T_s$ seconds, then its EqNS will backspace to N_{i-m}.

Considering the practical situation, the ΔT_s is taken as 10 s in this study. The last important point is that cockroach robots in practical using are inevitably carry electrical backpacks. Therefore, this study established the model of cockroaches under load (constant-current backpack and battery total weight 7.1 g).

Thirty cockroaches (13 males, 17 females, length and weight are not limited) evenly selected for acquisition experiment. The detail of experiment is in the last section of Chapter II .

B. Modeling

Sensitivity analysis can get the impact of different types of data on S-D-R model. Combination of orthogonal test and analysis of range was used to analyze the sensitivity in this work. The result is that Sex was 0.51, Length was 0.71, Weight was 0.58, Amplitude was 0.66 and EpNS was 0.44. Due to they did not differ from others by more than 0.26, weights of those were kept consistent in the modeling.

BP Neural Network is one of the most widely used neural network, which has powerful nonlinear mapping capabilities with highly self-learning. Fig. 3 decribes the neural network architecture of S-D-R model. There are 5 nodes(Sex, Weight, Length, Amplitude, Habituation) in input layer and 1 node in output layer. The number of nodes in hidden layer was choice as 18. The train algorithm was trainbr, the activation functions were tansig and purelin. The speed of study was set to 0.001 and the epoach was 3000.

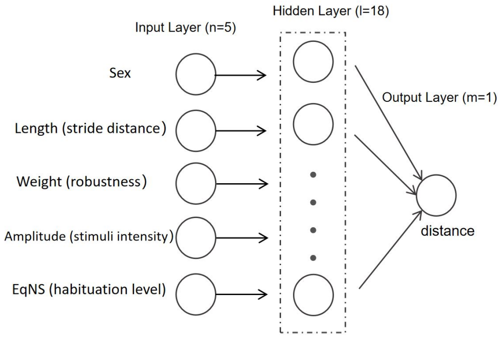


Fig. 3. Neural network structure in this study. All five inputs are factors that influence the distance traveled response. Length describes stride distance of cockroach, Weight describes robustness, Amplitude describes stimuli intensity and EqNS describes habituation.

Maximum EpNS in this model was choice as 135 since the EpNS hardly exceeds 100 in actual use. Sample size = 38 × 135, where 38 indicated trial number (two anomalous samples were eliminated). The order of all the samples was disrupted and training was done by taking 4104 samples from them.

IV. RESULTS AND DISCUSSION

A. The Response of Cockroaches to Bidirectional Constant-current Stimuli

1) Forward crawing speed response: Five cockroaches were evenly selected in each group. Fig. 4 shows cockroaches' forward crawing speed under bidirectional constant-current stimuli (Savitzky-Golay Fiter, w=19, k=3). There were 7 amplitude groups corresponding to 40-160 μA.

There was no significant increase in the forward crawling speed of cockroaches as the intensity of the constant-current electrical stimulus increased. At a current of 40 μA, only an average crawl speed of about 5 cm per second was achieved due to the weak electrical stimulus. As the intensity of the constant-current electrical stimuli continued to increase, the average speed of the cockroaches crawling forward all remained around 10 cm per second, but the number of effective controls gradually increased from 40 to 160 μA, as shown in Fig. 4(a)-(g). Fig. 4(h)-(i) shows the statistical analysis of all the data: when the constant-current intensity was 100 μA, the cockroach was able to have multiple control times and forward speed. Therefore, a parameter of 100 μA can be used as a forward control, and the intensity of the electrical stimuli was minimized.

2) Angle velocity response: Fig. 5 shows cockroaches' angle velocity under bidirectional constant-current stimuli(Savitzky-Golay Fiter, w=19, k=3). Lower constant-current stimuli has better turning control effect. When the constant-current was set to 80 μA, the turning angular velocity has been stabilized at about 50 degrees per second, as

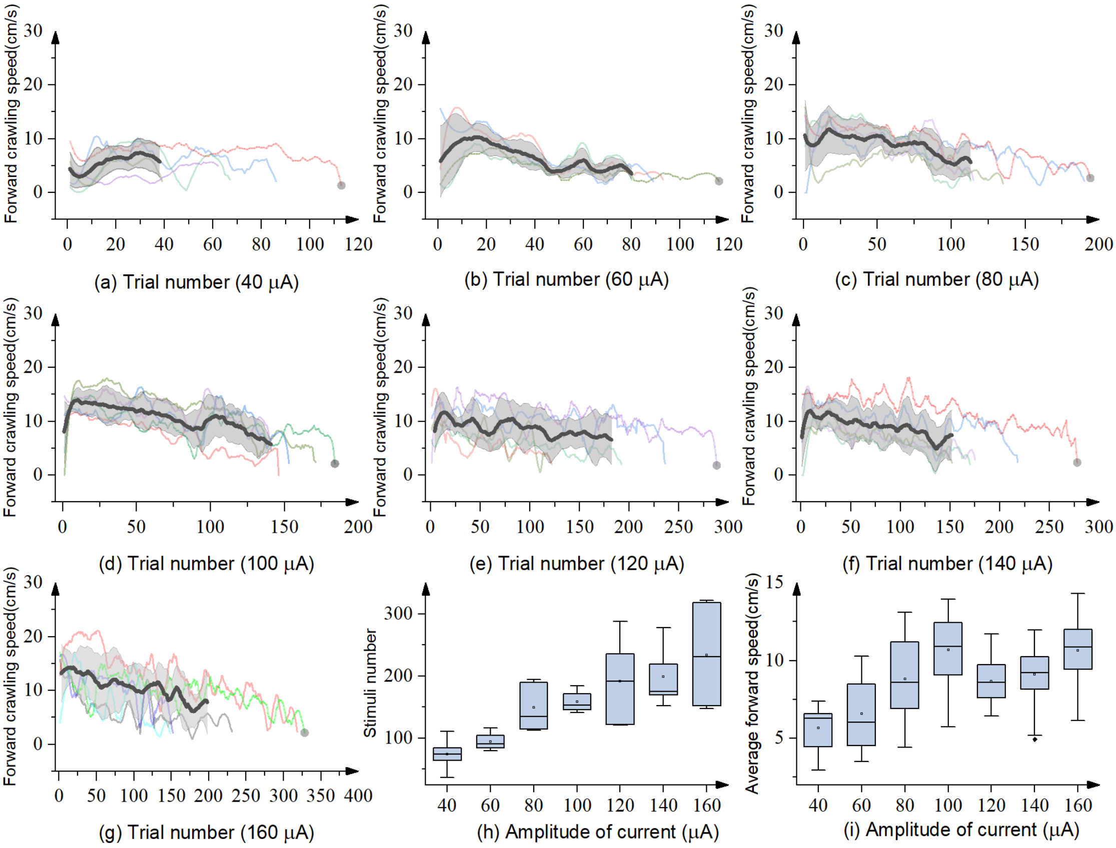


Fig. 4. The response of forward crawling speed under constant-current stiumli. Colour lines are forward crawling speed for each cockroach and black lines are the average speed (cut off at the least number of per group). (a)-(g) reflect the raw of velocity with the increasing stimuli number. The response can be divided into two stages: the activation stage and the decline stage. Cockroaches start with a moderate initial velocity, gradually accelerated in subsequent stimuli and reach the maximum velocity in the 5th-15th stimuli, then gone into decline stage. (h) represents the relationship between stimuli number and amplitude, they are positively correlated when the current amplitude was 40 μA, the average stimuli number was 74. It was 94.5 at 60 μA, 149.4 at 80 μA, 159 at 100 μA and 234.2 at 160 μA. (i) represents the relationship between average speed and amplitude. Maximum speed reached at 100 μA. The speed wouldn't reach a higher value due to the limitation of cockroach organism. 100 μA can already make cockroaches reach the maximum speed; when the current was in 140 μA and 160 μA, the speed increased relative to 120 μA, but the growth rate was not as fast as the growth rate in 40-100 μA.

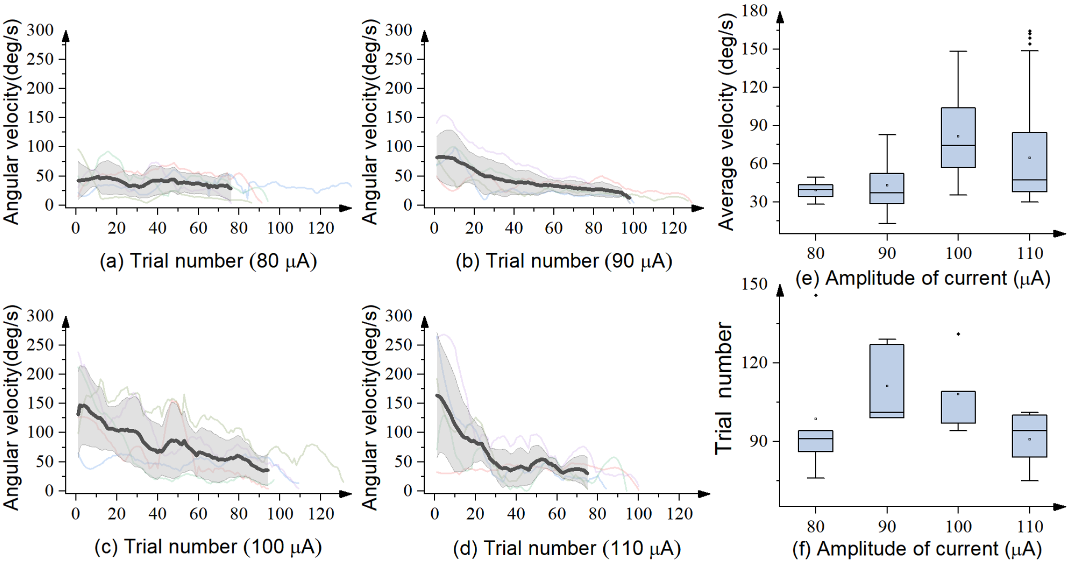


Fig. 5. The response of angle velocity under constant-current stiumli. Angle velocities bigger than 3 deg/s were reserved. Figures (a)-(f) reflect the raw of velocity with the increasing stimuli number. The curve was in a decaying state. (e) represents the relationship between average speed and amplitude. Maximum speed reached at 100 μA. (f) represents the relationship between stimuli number and amplitude. when the amplitude was 80 μA, the average stimuli number was 98.6. It was 111 for 90 μA, 108 for 100 μA and 90.8 for 110 μA. The maximum shows up at 90 μA.

shown in Fig. 5(a). The initial steering speed increased significantly with the gradual increase of the constant-current, and after a number of tests, a significant downward trend occurred. For example, when the constant-current was set to 110 µA, the turning speed 170 degrees per second dropped to 50 degrees per second after 40 trails, as shown in Fig. 5(d). Fig. 5(f) shows that when the constant-current was set to 90 µA, the cockroach was able to be controlled to turn for a longer time. But for turning, a steady rate of rotation would be more important than just having a high number of controls.

B. Comparison of Stimuli Effect between Optic Lobe Implantation and Antennae implantation

Six male cockroaches were tested, they were divided into groups of two. One group was optic lobe implantation and another group was antennae implantation. Fig. 6 shows the comparative stimuli effects results between optic lobe and antennae implantation (Savitzky-Golay Fiter, w=19, k=3). For antennae stimuli, the turning speed rapidly reduced from 55 degrees per second to 10 degrees per second after 15 trails. However, the optic lobe stimuli can induce turning movement at speed of 80 degrees per second and maintained turning speed of 40 degrees per second till 70 trials.

Optic lobe implantation method can increase the number of electrical stimuli effectively. In our previous studies, we were able to somewhat prolong the limited number by alternating the position of the electrical stimuli, but that method required more complex electrode circuit design and electrode implantation [12]. Optic lobe implantation was able to effectively control the turning for a long period of time, which was important for the practical application of biological robots.

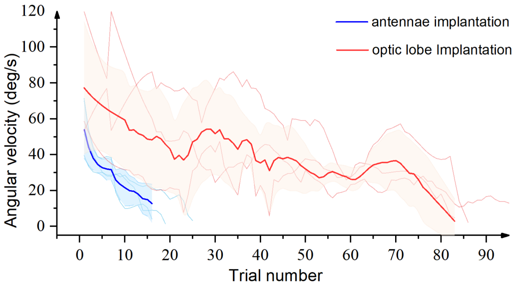


Fig. 6. Comparison of turning control effect for two kinds of implantation. Turning control of antennae reduced rapidly to 15 degrees per second after 15 trails. For optic lobe implantation, it can achieve effective control up to 70 times.

C. Validation of Cockroach Bio-robot Forward Crawling Stimuli-distance Response Model

1) Model Validation Without Backspace: no EpNS backspace is a more desirable uniform situation. That means during the working process, cockroach bio-robot will inevitably receive the next command within 10 s after receiving a command. Input the remained 1026 data untrained to model, obtaining predicted value than comparing them with the truth to verify the model in this scenario. Fig. 7(a) describes the results. The ratio of samples whose relative error less than 5% are 63.64% and less than 10% are 86.25%. In addtion, when EpNS is small, the accuracy of model is particularly critical due to it is impossible for EpNS to achieve a high level in practical use. The samples whose EpNS are 1-10 were selected and shown in Fig. 7(b). The relative error of 77.11% samples are less than 5% and 92.78% are less than 10%. The model is particularly accurate when EpNS is small.

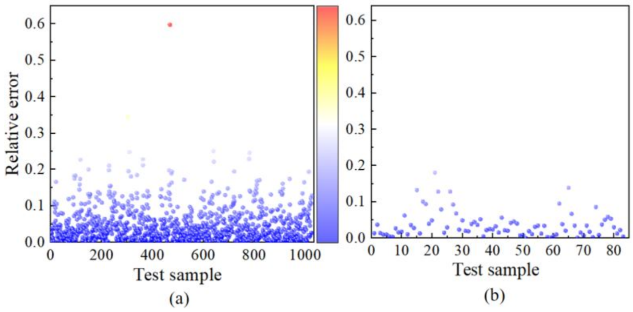


Fig. 7. Model relative error without backspace. (a) describes validation results for all samples. The total sample number is 1026. There are 653 samples with relative error less than 0.05, accounting for 63.64%; 232 samples are between 0.05-0.10, accounting for 22.61%; 127 are between 0.05-0.10, accounting for 12.37%; 13 are between 0.20-0.30, accounting for 1.267% and 1 are higher than 0.5. (b) shows results for samples whose EpNS are between 1-10. The total sample number is 83. There are 64 samples with relative error less than 0.05, accounting for 77.11%; 13 samples are between 0.05-0.10, accounting for 15.67%; 5 are between 0.05-0.15, accounting for 6.04% and 1 is between 0.15-0.20.

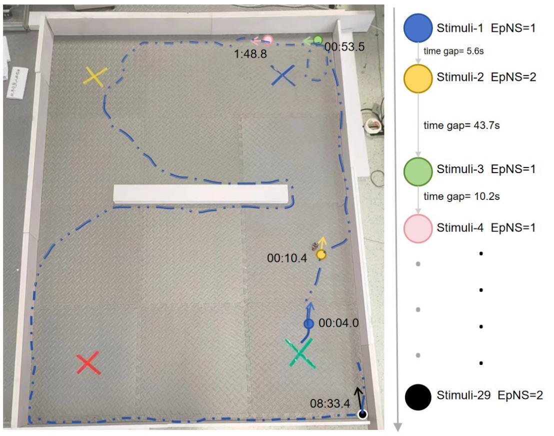
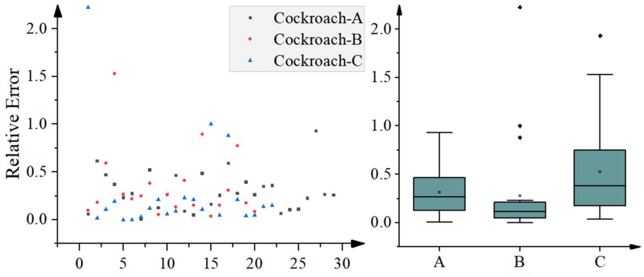


Fig. 8. Practical working scenario. Here is a 3 m×4 m area with obstacle. The bio-robot's task was travelling to the four marked points in turn. The robot in picture is cockroach-A, its motion trajectory is marked with a blue line. cockroach-A was stimulated 29 times, the information of its first four and last stimuli are excerpted in the figure and marked with colored dot.

2) Model Validation In Practical Situation: Fig. 8 shows a working scene. There are four marked locations in a 3 m×4 m area with an obstacle in the center. The cockroach robot was remotely controlled and traveled to these four locations in turn. Cockroach-A(3.571 g, 54.63 mm, female, 100 uA), cockroach-B(3.073 g, 49.58 mm, male, 120 uA) and cockroach-C(3.582 g, 51.01 mm, female, 140 uA) participated in the experiment. Fig. 9 shows the relative error between the predicted distance of model and the actual distance of three cockroaches. Their median relative error are respectively 26.2%, 23.5%, 11.5%.



(a) (b)

Fig. 9. Relative error of the predict and the truth in practical experiment. (a) shows the relative error of each stimuli during working. (b) shows the error bar of each cockroach. All abnormal points (such as cockroaches hitting the wall, getting stuck, etc.) were considered part of the actual scene and their data were remained. The average relative error of A is 29.7%, its median relative error is 26.2%; for B these two indicators are 34.7% and 23.5%, for C are 27.8% and 11.5%.

V. CONCLUSION AND FUTURE WORKS

In this work, we proposed a new low habituation method and build its response model. Optic lobe implantation was proposed and it lasted longer than traditional methods. Meanwhile, a new backpack can stably release bidirctional constant-current has been designed and the response law for cockroach to constant-current was summarized. The current amplitude for forward motion is recommended as 100uA. Our model was established based on cockroaches under load. In the case of continuous stimuli, 63.64% of the 1026 test samples had a relative error of less than 5% and 86.25% less than 10%. When predicting 83 samples whose EpNS are between 1-10, the proportions of two items increased to 77.11% and 92.78%. In work scenario testing, the median relative errors of three bio-robots are respectively 26.2%, 23.5% and 11.5%. The result meet the requirements and characteristics of bio-robots.

The stimuli response model for cockroach robots has been established, which is of great significance for control. So in the future works, automatic control algorithm will be used and the experiment will be conducted in more complex scenarios. Definitely, the model will be kept expanding, more output such as speed will be put to enrich this model.

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