BIOBOTIC MOTION AND BEHAVIOR ANALYSIS IN RESPONSE TO DIRECTIONAL NEUROSTIMULATION

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ABSTRACT

This paper presents preliminary results for motion behavior analysis of Madagascar hissing cockroach biobots subject to stochastic and periodic neurostimulation pulses corresponding to randomly applied right and left turn, and move forward commands. We present our experimental setup and propose an unguided search strategy based stimulation profile designed for exploration of unknown environments. We study a probabilistic motion model fitted to the trajectories of biobots, perturbed from their natural motion by the stimulation pulses. Furthermore, we provide a statistical assessment of the biobotic directional response to turn commands and its correlation with stimuli profile over time. This study paves the way towards reliable control for more realistic under-rubble search and rescue applications.

Index Terms— Biobots, Behavior Analysis, Motion Modeling, Neurostimulation, Random Walk

1. INTRODUCTION

Biobots are live instrumented insects whose locomotion can be controlled by means of neural or muscular stimulation [1–6]. Current trends and advances in neural engineering have enabled researchers to develop such biobots for use in search-and-rescue. We have had success with the Madagascar hissing cockroaches (*Gromphadorhina portentosa*) as biobots through several laboratory-based biobotic experiments where we used electronic backpacks to generate the required neurostimulation at the antennal tissue-electrode interface [1, 2, 7, 8]. Cockroaches can display an effectual navigational capability and adaptability in dynamic environments along with instinctive reaction to escape obstacles [9]. Therefore as instrumented "working" animals, roach biobots can be employed as a complementary platform to centimeter-scale robotics.

A sensor network of these biobots, with each biobotic backpack acting as a sensor node, can be dispersed under rubble in a disaster area. The intended network can be potentially used for mapping and monitoring the disaster area [8, 10–12], search for survivors using acoustic sensors [2], and assist first responders with useful information. These types of real life tasks require a reliable and efficient system. Part of our research involves developing an effective mapping framework with a network of *actively moving* biobots. Although cockroaches are well-known for their efficient exploration strategies by manifesting random walk and wall following strategies as part of their natural behavior, they spend a great portion of time in a *stop* mode, in which they remain stationary (i.e. not moving) [13, 14]. This will degrade the performance in terms of the amount of sensor information collected from search and rescue environments in a given interval of time.

For this purpose, in this paper we propose an exploration strategy by applying stimulation pulse trains randomly to either an antennae or cercus of cockroach biobots at regular intervals in order to have them move continuously, thereby keeping them in their *active* mode. Random strategies for search and exploration have been extensively used in motion planning for robotic systems [15]. Such strategies will eliminate the requirement of a continuous human supervised feedback control under rubble when wireless communication with biobots is susceptible to dropouts. Characterization of the spatial motion of the biobots in their natural and controlled mode plays an important role in the performance and estimation accuracy of the developed mapping algorithms [16]. Furthermore, directional steering of biobots toward their left or right via stimulation of their right and left antennae respectively, together with utiliza-



Fig. 1. Experimental system setup showing a roach biobot, with a neurostimulation backpack, moving in a circular arena and observed with a camera; $\Delta \theta$ denotes angular change of biobot's position in response to antennal stimulation. Computers are used for (1) visual recording and processing and (2) logging applied stimulus commands. An overview of the random directional stimulation pulse profile (top right) with N = 6 repetitions for left and right stimulation and N = 1 repetition for forward stimulation.

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tion of an invisible fence algorithm [7], are essential components for herding a swarm of biobots for global mapping of complex environments [12]. As such, we characterize the locomotion of biobots subject to the proposed random directional stimuli with a probabilistic motion model, inspired by the existing biological models for natural behavior of cockroaches [13, 14]. In addition, we study directional response of the biobots to turn signals and their correlation over temporal windows, in order to assess biobotic directional control capabilities and optimum stimulation strategies. Such analysis will provide grounds for the design of biobotic algorithms that are stable and reliable in real life scenarios.

2. BIOBOTIC EXPERIMENTAL SETUP

2.1. Biobots and Neurostimulation Backpack

The experiments were carried out using nine female hissing cockroaches from a lab-reared colony, exposed to a reverse day-night cycle. The biobotic transition process for these cockroaches involves surgical implantation [2] of PFA-insulated 127 μ m diameter stainless steel wire electrodes (A-M Systems) into the flagellum of each antennae and a cercus of an anesthetized cockroach as working electrodes, with a fourth electrode into the mesothorax as the common electrode. An electronic neurostimulation backpack, mounted on the dorsal part of a recuperated cockroach (Fig. 1), selectively stimulates the antennae to steer the cockroach in desired directions [1, 2, 7, 8]. The directional change in locomotion is evident from an angular change of the cockroach in response to the antennal stimulation. Cercal stimulation induces a forward-moving response in the cockroach.

The neurostimulation backpacks are made with commercial off-the-shelf components, including an on-board system-on-chip (CC2530 from Texas Instruments), and weigh well below the payload capacity of the roaches [2]: about 0.3 g without battery and about 1.8 g with a 50 mAh lithium polymer (Li-Po) battery. The backpack runs a low-power Contiki operating system with which we have achieved automated and random control of multiple biobots. Our previous biobotic experiments were carried out using both a single biobot [1, 2, 7, 8], and simultaneous and manual control of multiple biobots [17]. In this study, we expanded on that work for accommodating automated control, with capability to generate stimulus at random. The backpack is programmed to generate a 3V monophasic electrical pulse train of 5 \times 50 ms at 50% duty cycle, with N repetitions after short delays of $d_{sh} = 300$ ms. For an antennal stimulus, we tried N = 6, and for a cercal stimulus N = 1. For randomly generated stimulus, a long delay of $d_l = 5$ s is applied between each stimulus (Fig. 1 - top right). At the end of each long delay, the next command is selected randomly as either left (L) or right (R) antennal stimulation (each with a probability of 0.2) or cercal stimulus with a probability of 0.6. A continuously and randomly generated stimulus profile ensures a non-stationary biobot moving in random directions.

2.2. Experimental Setup

In this work, we use our system for automated control of a single biobot, collect relevant biobotic locomotion data, and use the data in developing the biobotic model. Fig. 1 shows an overview of our experimental setup, where a camera (Microsoft LifeCam HD-5000) is oriented to look down at a circular arena with a diameter of 115 cm. A CC2530 module on a SmartRF05 evaluation board (both from Texas Instruments) acts as the stimulation commands transmitter. Issued commands are displayed on a command window and recorded



Fig. 2. (a) A screenshot of a video used for visual tracking and synchronization showing a tracked biobot in the arena, illustration of partitions C and P, RW and WF behaviors, and (inset) template used for received stimuli extraction. (b) Trajectory of a biobot obtained in post-processing. Video of a biobotic trial can be found online.¹

on a computer, through PuTTY, connected to the evaluation board via a serial cable. The camera is connected to a second computer which records the experiment as well as stimulation commands from the screen of the first computer.

We ran our experiments at the same time of the day in the afternoon (nighttime for the roaches) and under the same lighting conditions for the purpose of consistentcy. A trial lasted until the biobot stopped moving for a period longer than 30 s, possibly due to added weight of the backapck or by the duration of the experiment itself. A resting period of at least half an hour was allocated to a biobot before using it in a subsequent trial.

3. METHODOLOGY

3.1. Data Preprocessing

The trajectory and orientation of a biobot is tracked and synchronized with stimulation commands via automated processing of videos.

Visual Tracking: Positional and angular tracking of the biobot are extracted from the videos employing a visual tracking technique by background subtraction and threshold based segmentation of the regions corresponding to the biobot. The (x, y) coordinates and the orientation θ of the biobot in the space are obtained from the center of mass and principal direction of an ellipse fitted to the segmented regions.

Visual Time Synchronization: In order to synchronize temporal information of the recorded trajectories with stimuli time stamps, we acquire a frame labeling procedure by displaying the received signals by the roaches at each frame as shown in Fig. 2(a) - top left, and perform a binary template matching to identify the corresponding command. This eliminates the need for clock synchronization between the camera and CC2530 transmitter/receiver.

3.2. Behavior Analysis

3.2.1. Biobotic Movement Model

Cockroaches' *natural* individual activities in bounded spaces can be described by a model composed of the following *modes* of behavior [13, 14]: random walk (RW), wall following (WF), and stop (S). They typically perform a random walk motion when they are far

¹Online link: https://youtu.be/nJiOPr4rkxw.

enough from the boundaries of the domain, and start a wall following behavior when they detect the edges of the environment using their antennas [13, 18]. Insects intermittently move and stop during RW and WF behaviors, which are natural strategies used by roaches for search and exploration. These modes are preserved in biobots while the corresponding models and parameters for statistics of their motion alter. For our analysis, we divide the arena and corresponding trajectories into two partitions: *peripheral* (P) and *central* (C) (Fig. 2); partition P is defined as the subspace $r_p = 4cm$ from the boundary of circular domain. We label the trajectories accordingly, and model each mode separately with corresponding statistics of transitions.

RW motion, popular among various types of biological systems, can be classified into several variations: *Levy walks* [19], *correlated random walks* (CRW) [20], and *diffusive random walks* [13], depending on the distribution fit to the movement data. In this paper, we propose to fit a CRW model to the *biobotic* motion in partition C. In CRW model, the movement is described as a series of piecewise linear steps with fixed orientation, characterized by line segments l_i , interrupted by changes in direction ϕ_i (see Fig. 1(b)). The lengths of line segments l has an exponential distribution with characteristic length l^* :

$$p(l) = l^{*-1} e^{-l / l^*}.$$
 (1)

Unlike Levy walk and diffusive random walk in which the changes of directions are uniformly distributed, in CRW the ϕ_i 's are drawn from a circular distribution peaked at 0 (e.g., Mises distribution [21]), which indicates directional persistence [22].

The WF mode is triggered by entering partition P (an eventtriggered mode) from where biobots switch back to the CRW mode towards partition C stochastically, with a probability of p_{exit} , due to their responses to natural or biobotic stimuli. The S mode, on the other hand, is characterized by a transitional probability p_{stop} from a moving mode (CRW or WF), as well as the statistics of the duration of stop intervals. We consider a unimodal S mode with an average characteristic time of τ_{stop} . We label the biobots' activity as an S mode if the directional change over a window of length $w_t = 1$ second is less than $\theta_d = 10^\circ$ and its displacement is less than $\delta_d = 0.5cm$.

Turn Identification and Path Segmentation: An imperative step towards fitting movement models to biological trajectories is to segment the path into discrete relevant steps based on a spatiotemporal criteria. Such discretization of the movement path is usually subjective to the choice of observer. A common method [23] is to identify significant turn events (changes of direction) in the trajectory and split the path into series of segments between those turning points. Turn event identification is also a selective process depending on the interpretation of the observer. There exist a variety of turn identification methods, and acquiring a proper technique depends on the interpretation of a human observer. Among such techniques, local methods, which detect turns between all successive samples, are sensitive to sampling scale, and *cumulative* approaches are preferred. The effect of turn identification on CRW model has been studied in [20]. In this paper, we first filter out paths labeled as WF. Then for the segments in partition C, cumulative changes of angles $\delta \theta_i$ over time windows $[t_i, t_i + w_t]$ are measured, and the ones over a threshold τ_{θ} are marked as the initial set of turn events. From this set, those which belong to consecutive windows are grouped as single turn events. Transition points from WF to CRW and from CRW to WF are then added as start and end points of corresponding segments. The average velocity in partition C is calculated as $v_m = \sum l_j / t_j.$

3.2.2. Stimulant Response Analysis

We investigate the response of biobots to turn commands left (L) and right (R) over temporal windows of lengths $\Lambda = N_{L/R}(T_s + d_{sh}) + d_l$ starting from the moment each stimuli was received, which covers the intervals from the beginning of an impulse up to the start of the next one. We define $\Delta \theta_L^i(\lambda)$ as the angular change towards left evoked by stimuli to right antenna, after a delay of λ seconds as:

$$\Delta \theta_L^i(\lambda) = \theta(t_L^i + \lambda) - \theta(t_L^i), \tag{2}$$

where $\theta(t_L^i)$ is the angular change corresponding to time t_L^i when the i'th R-stimuli was applied. $\Delta \theta_R^i(\lambda)$ can be expressed in a similar manner. Statistics of angular change provide insight on the response of biobots to neurostimulation. An applied stimuli is deemed successful if the average value of $\Delta \theta_L^i(\lambda)$ (or $\Delta \theta_R^i(\lambda)$) for $\lambda \in [0, \Lambda]$ is positive (or negative). The success rates η_L and η_R for each stimuli are calculated as the portion of successful turns over all trials.

Correlation Analysis: We are further interested to investigate correlation between stimulation pulse trains and angular response with variation of delay parameter λ . To do so, we generate a stimuli pulse train as $S(\lambda) = S_L(\lambda) + S_R(\lambda)$, where

$$S_L(\lambda) = \begin{cases} +1, & \lambda \in [t_L^i, t_L^i + \Lambda - d_l] \\ 0, & \text{otherwise,} \end{cases}$$
(3)

and $S_R(\lambda)$ is defined in a similar manner for R stimulation where the amplitude is -1 over $[t_R^i, t_R^i + \Lambda - d_l]$ and 0 otherwise. The normalized variations of angle with delay λ is defined as $\omega(\lambda) = \omega_L(\lambda) + \omega_R(\lambda)$, where

$$\omega_L(\lambda) = \begin{cases} (\theta(t_L^i + \lambda) - \theta(t_L^i))/\lambda, & \lambda \in [t_L^i, t_L^i + \Lambda - d_l], \\ 0, & \text{otherwise,} \end{cases}$$
(4)

and $\omega_L(\lambda)$ is defined in similar manner. We then measure the correlation between stimulation *S* and angular observation ω as $\rho_{\lambda} = \frac{\operatorname{cov}(S,\omega)}{\sigma_S \sigma_{\omega}}$, where σ_S and σ_{ω} refer to the standard deviations of *S* and ω .

Boundary vs. Free Space: For analyzing biobotic response to stimuli, we differentiate between cases when biobots can freely move in a space (usually in partition C) and when the arena boundary acts an obstacle (usually in partition P) restricting angular turns. The latter however depends on the orientation of the biobot during WF (CW or CCW) and the stimuli: L or R. Particularly, in cases when the biobot is in a CW-WF (CCW-WF) mode and receives an L (R) turn command, it cannot make a proper turn as the boundary acts as an obstacle. On the other hand, in the cases of CW-WF,R and CCW-WF,L the boundary is expected to not interfere with an angular response.

4. EXPERIMENTAL RESULTS

We collected 5 hours of biobotic and 6 hours of natural experimental data for a total of 39 trials with 9 biobots, with the average length of each trial being about 9.16 minutes.

Movement Analysis: Trajectories and orientation of biobots as well as the received commands are extracted and synchronized, and each frame is labeled as CRW, WF, or S (in C or P) mode. Table 1 summarizes statistics of various determining factors in motion behavior analysis of biobots compared to natural roaches: μ and σ refer to the mean and standard deviation of each parameter over all trials.

(a) Biobotic Motion Parameters							
	\mathcal{F}_C	p_{exit}	l^* (cm)	v_m (cm/s)	\mathcal{F}_{move}	p_{Stop}	τ_{stop} (s)
μ	0.599	0.052	8.714	2.49	0.643	0.107	5.55
σ	0.250	0.097	3.848	0.714	0.190	0.200	3.34
(b) Natural Motion Parameters							
	\mathcal{F}_C	p_{exit}	l^* (cm)	v_m (cm/s)	$\mathcal{F}_{\mathrm{move}}$	p_{Stop}	$\tau_{\rm stop}$ (s)
μ	0.632	0.005	17.586	1.94	0.372	0.211	36.77
σ	0.165	0.001	4.79	0.29	0.199	0.099	24.08
(c) Angular Response Characteristics (Free Space)							

 $\Delta \theta_{I}^{\Lambda}$

26.22

22.76

 η_L

0.741

0.228

 η_R

0.736

0.447

 λ_{max} (s)

1.403

0.368

 $\Delta \theta^{i}$

 μ

 σ

46.04

25.56

 $\Delta \theta_{R}^{ma}$

-41.36

38.78

 $\Delta \theta$

24.61

21.55

 Table 1. Experimental behavior analysis results for 33 trials with 9 biobots

The first two columns represent behavioral characteristics with regards to motions in partitions C and P. \mathcal{F}_C denotes the portion of mean time the biobots spend in partition C in each trial. It can be observed that our stimulation strategy does not have any major impact on the average \mathcal{F}_C , despite causing larger variations compared to the natural motion. This can be justified by the roaches' strong natural tendency to follow the walls. The average probability of exit, p_{exit} , increases in the biobotic mode, indicating a higher chance of biobots returning to C from P. Designing strategies for controlling \mathcal{F}_C is left as future work, and could be achieved by including sensors (e.g., inertial) that help identify boundary motion.

Fig. 3 presents the distribution of turn angles ϕ_i (left) and lengths of path segments (l_i) for a single biobotic trial. The distribution of turn angles peak around zero and l_i follows an exponential distribution as expected in the CRW model. Characteristic lengths l^* for each trial are fit using maximum likelihood, whose statistics are reported in Table 1. It can be seen that l^* for biobotic motion decreased by a factor of about 2, which can be attributed to regular turn commands. The mean velocity over the biobotic trials increased by a factor of 1.28 with increased deviation, and can be attributed to the effect of stimuli. This is consistent with the the fact that the maximum velocity observed for biobotic mode is around 11.6 cm/s versus around 7.6 cm/s in their natural mode.

The last three columns in Table 1 characterize the stop behavior of the roaches in their active mode. \mathcal{F}_{move} denotes the portion of mean time the roaches are moving. It can be seen that both \mathcal{F}_{move} and p_{stop} improved by a factor of 2 in the biobotic mode. Lastly, characteristic time of stops (τ_{stop}) decreased significantly in biobotic mode.

Angular Response Analysis: Fig. 4 presents the angular variation $\Delta \theta_L^i(\lambda)$ and $\Delta \theta_R^i(\lambda)$ in response to right and left antennal stimulation, respectively, for a single 17 minutes long trial where a total of 37 R-antennal and 47 L-antennal stimuli were received by the biobot. For precise analysis, we labeled each turn as a boundary or a free space case based on the discussion in the previous section. As expected, the biobotic angular change was towards left $(+\Delta\theta)$ for most of the R stimulation (78%). From the 22% negative turns, 13.75% occurred possibly due to close proximity to the boundary as an obstacle (CW-WF shown as orange curves), while the rest due to its natural instincts possibly overriding applied stimuli. For the L stimulations, 76.6% resulted in right turns (- $\Delta\theta$), while 8.5% resulted to left turns in obstacle boundary cases (CCW-WF, R). In this particular trial, angular response due to L stimulations was observed to be relatively better than R stimulations, and can be possibly attributed to difference in electrode implants.



Fig. 3. Histogram of typical biobotic turn angles (left) and correlated random walk segment lengths (right).



Fig. 4. (a, b) Variation of angular change over delay λ : (a) L-turn (positive $\Delta \theta$) in response to R antennal stimulus and (b) R turn (negative $\Delta \theta$) in response to L antennal stimulus. The mean angular variation in each case is plotted as a red curve. (c) Correlation between the stimuli signals S_L , S_R and S with angular response over time. The peak value for ρ_{λ} is shown as a red circle.

The correlation between the stimuli and angular change, ρ_{λ} , over a window of $[0, \Lambda]$ was plotted, as shown in Fig. 4(b). A maximum correlation was observed for a lag of $\lambda_m^{\rho} = 1.81$ s, indicating the maximum effect of antennal stimulation occurred at an average of 1.81 seconds after initiation of the stimuli. Statistics of angular response characteristics for all trials, excluding obstacle boundary cases, are summarized in Table 1(c). $\Delta \theta_L^{max}$ and $\Delta \theta_R^{max}$ represent the maximum angular change observed towards L or R over temporal windows $[0, \Lambda]$, and $\Delta \theta_L^{\Lambda}$ and $\Delta \theta_R^{\Lambda}$ denote the amount of change after Λ seconds. Although the resultant angular changes observed in response to proposed stimulation profile proved to be satisfactory, with some obvious directional variations, further investigation on external parameters affecting biobotic response to motion commands is required towards a more robust and reliable system.

5. CONCLUSION

We proposed a random stimulation strategy that may be effectively used for exploration of unknown environments by a network of biobots. In this work, we characterized biobotic random motion, elicited by applied neurostimulation, through analysis of biobotic positional information and behavioral models. Incorporating research on external factors affecting biobotic operation [24], we will further investigate biobotic motion behavior towards ensuring a robust and reliable system.

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