Line Following Terrestrial Insect Biobots

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***Abstract*—The present day technology falls short in offering centimeter scale mobile robots that can function effectively under unknown and dynamic environmental conditions. Insects, on the other hand, exhibit an unmatched ability to navigate through a wide variety of environments and overcome perturbations by successfully maintaining control and stability. In this study, we use neural stimulation systems to wirelessly navigate cockroaches to follow lines to enable terrestrial insect biobots. We also propose a system-on-chip based ZigBee enabled wireless neurostimulation backpack system with on-board tissue-electrode bioelectrical coupling verification. Such a capability ensures an electrochemically safe stimulation and avoids irreversible damage to the interface which is often misinterpreted as habituation of the insect to the applied stimulation.**

I. Introduction

A. Biobotic Control of Insects

Autonomous navigation in unknown and dynamic environments has been a major challenge for mobile robotic systems. The challenge is scaled up as the size of the robots is scaled down to centimeter scale due to difficulty of implementing and controlling locomotion at minuscule scales. Insects, on the other hand, can easily and stably navigate through almost any environment. The recent developments in neuromuscular stimulation research have been used to navigate the aerial insect locomotion to enable insect biobots [1]-[14]. In these studies, electrical pulses were applied to the insect to create biomechanical or sensory perturbations in the locomotory control system to steer it in desired directions, similar to steering a horse with bridle and reins. These biobots can potentially assist humans in environmental sensing and search-and-rescue applications to pinpoint hazardous material or to find earthquake victims.

In our earlier studies, we were able to initiate and cease flight, and induce yaw maneuvers in tethered and lift assisted hawkmoths [2]-[7] by stimulating the direct flight muscles, antennal lobe and neck muscles. We were also able to decrease the take-off duration by implanting micro-heaters into the insect thorax [8]. We also achieved control of terrestrial locomotion on hawkmoths on a two-dimensional foam-ball treadmill and on flat surface where insect followed the left and right turn signals [3],[6]. Tactile, thermal and electrical stimulation of cockroach antennae by other groups also caused a turning action towards the opposite direction of the stimulated site on "tethered" set-ups [15]-[18]. Here, we present wireless electrical stimulation of free-walking cockroaches for precise navigation where the biobots were made to follow lines.

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Figure 1: Assembled system-on-chip based backpack with Flexible Flat Cable (FFC) connectors added for battery and probe connections. The system is implanted on a cockroach.

B. Natural Locomotory Control System

Like most other insects in their order (Blattaria), cockroaches have two antennae, two cerci at the rear end of their body and three pairs of legs as the main anatomical structures of their sensorimotor system. Roach antennae are multifunctional sensors to sense olfactory, tactile, thermal, and humidity cues. Roaches may navigate and detect obstacles through the use of their tactile senses in particular. Although, cockroaches benefit from multiple sensory organs, their navigation primarily relies on the antennae, especially during the escape response where the visual and other senses cannot respond as fast [19]. Their antenna is divided into three parts: the scape, the pedicel, and the multi-segment flagellum (Figure 2). Upon encountering an obstacle or a predator, sensory input from the flagellum to the nervous system elicit turning and/or running behavior [20]. Therefore, cockroaches make turns accordingly depending on the orientation of the antennae [1]. Cerci, on the other hand, are fine hair-like appendages at the rear which move at the slightest variation of the air present at the rear of the cockroach. Based on the level of this sensory input, escape mechanism may be elicited to avoid predators.

C. Simulating Obstacles as a Navigation Strategy

The basic exterioceptive strategy to navigate a cockroach through a trajectory would be to simulate obstacles at the bend of the trajectory and hence make the cockroach turn. Selective manual stimulation of one or both antennae with electrical pulses would make it take a turn in the desired direction accordingly.

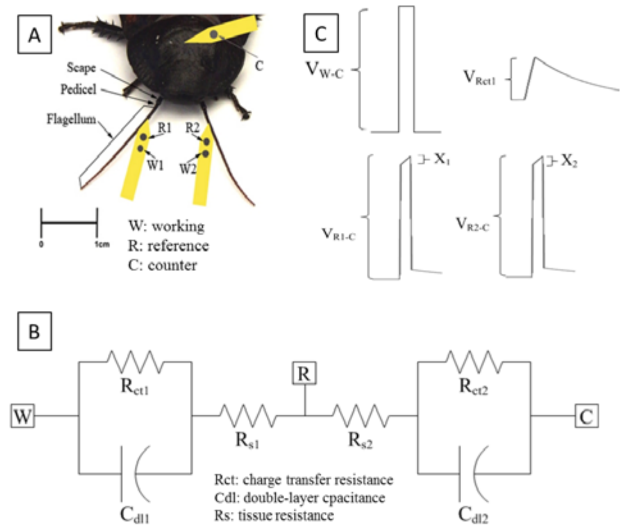

Figure 2: (A) Anatomical parts of the cockroach antenna and diagram of proposed three electrode measurement set-up to assess the voltage across the tissue electrode interface. (B) The equivalent circuit of the tissue electrode interface. (C) PSpice simulation output of voltages between working, reference, counter electrodes and across the tissue electrode interface.

II. Materials And Methods

A. Model Insect

Gromphadorhina portentosa, also known as the Madagascar Hissing cockroach, was selected as the model insect for this study. It's relatively larger size (~50-75mm), slower speed (~3cm/s), longer life span (~2 years), agility and robustness made it an ideal candidate for the experiments. These insects are commercially available in the US [21].

B. Surgical Implantation

Stainless steel electrodes, in the form of 200µm-diameter wires coated with 250µm-thick Teflon® PFA insulation, were selected to apply the stimulation pulses. Strands of 5cm wires were taken and the insulation was removed at either ends for about 3mm. One of the ends was soldered to a printed-circuit board to be connected to stimulation electronics. The other end was inserted into the cockroach antenna. For effective insertion and minimally disturb the insects, cockroaches were anesthetized by cold-treatment (4°C) for 45-60 minutes. Then, the flagellum of both the antennae was partially removed for insertion of the active electrodes to either antenna. The depth of insertion was determined by the lines marked on the electrodes. The insertion points were sealed off with synthetic glue. The third, ground, electrode was placed in the ganglia by inserting it through the first segment of the thorax through an incised hole. The cockroach was left to recuperate before experimentation could begin. High ethical standards were followed during the treatment of the insects [22]-[23].

C. Radio Controlled Neuro-stimulator

For proof-of-concept experiments, a heavier stimulation system based on PIC16F630 [24] microcontroller with IA4320 ISM Band FSK receiver was used in conjunction with a commercially available HFX 900 transmitter. The user sent right or left turn commands remotely through the joystick on the transmitter. The receiver on the insect backpack demodulated the pulses and delivered to the microcontroller. The generated 3-volts DC stimulation pulses were applied to either antenna through the indwelling electrodes for eliciting turning action on the cockroach. The insect backpack consisted of a thin rigid printed circuit board (PCB) with assembled microcontroller, receiver, miniature plugs to connect the stimulation electrodes and a 90mAh Li-Po battery. The system weighed 4g, where the backpack was around 1g and battery was 3g. The system can be seen on the insect (Figure 3).

A system-on-chip based light-weight solution was also devised using the Texas Instrument's CC2530 [25] to replace the heavier system. The weight of this backpack (Figure 1) is only 500mg. CC2530's 21 general purpose I/O pins allows for addition of stimulation channels to the experimental design.

D. On-board Tissue-Electrode Coupling Verification

During the biobotic applications, the bioelectrical coupling between the tissue and electrodes is prone to fail temporarily or permanently due to the delicacy of the tissue-electrode interface [9]-[11], [26]. The resulting insensitivity may be misinterpreted as habituation of the insect to stimulation pulses. To verify the reliability of this coupling, we developed a microcontroller based procedure thanks to CC2530's extra analog-to-digital converters available on-board. The three electrodes implanted in the insect for stimulation (right, left and ground) were used as a three electrode electrochemical cell (Figure 2). The procedure involves the analysis of induced voltage excursions across the electrode-tissue interface to keep it within a safe range [26]. For this, an input voltage pulse was applied between the stimulation (working) and ground (counter) electrodes, while we monitored the voltage between reference electrode and the counter electrode. The equivalent circuit model (Figure 2) allows us to estimate the voltage across the tissue electrode interface by the voltage between the reference and counter electrodes [10]. The voltage across the working electrode-tissue interface (R_{ct1}) and counter electrode-tissue interface (R_{ct2}) can be found by (see Figure 2):

$$V_{Rct1} = \frac{V_{R2-C}X_1 - V_{R1-C}X_2}{V_{R1-C} - V_{R2-C}}$$
$$V_{Rct2} = \frac{(V_{W-C} - V_{R2-C})X_1 - (V_{W-C} - V_{R1-C})X_2}{V_{R1-C} - V_{R2-C}} \quad (1)$$

The operation needs to be ceased if the voltage across the interface is above the water window (>0.7V) [26]. Only a portion of the applied 3.5V drops across the tissue electrode

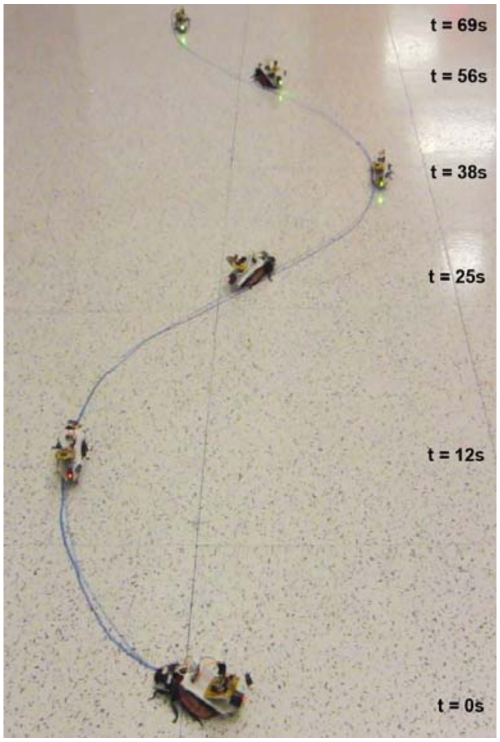

Figure 3: The snapshots from the recorded video [27] of remote controlled line following roach biobot

interface and this procedure makes sure that the voltage drop is below 0.7V to avoid O_2 evolution which may cause irreversible damage to the interface.

III. Experimental Results and Discussions

Cockroaches with the backpack system were made to follow an S-shaped trajectory drawn on the laboratory floor while the results were video-recorded (Figure 3). The stimuli were applied to the appropriate antenna of the cockroach based on visual feedback of the operator. Figure 4 shows the trajectory on the floor with superimposed arrows showing relative position of the cockroach at different time steps during a typical successful experiment. The green arrows show the direction of the insect before left-turn stimulation and the red arrow indicates the direction before the right-turn stimulus. The after-stimulus position is indicated with a black-arrow for both cases. The duration of applied stimulus are also presented on the same graph for a typical demonstration, in addition to the duration and amount (in degrees) of resulting rotation maneuver. The cockroaches were also made to repeat the same task by walking in the opposite direction. A typical experiment with roach walking in both directions can be found in [27] as a video.

During these experiments, it was observed that the cockroach moved in an almost straight trajectory until a stimulus was applied. Upon application of the stimulus, cockroach briefly stopped assuming existence of a barrier or a predator, and then took a turn accordingly. The angular speed is defined as the induced change in the direction-angle around the yaw (vertical) axis with respect to the turning time.

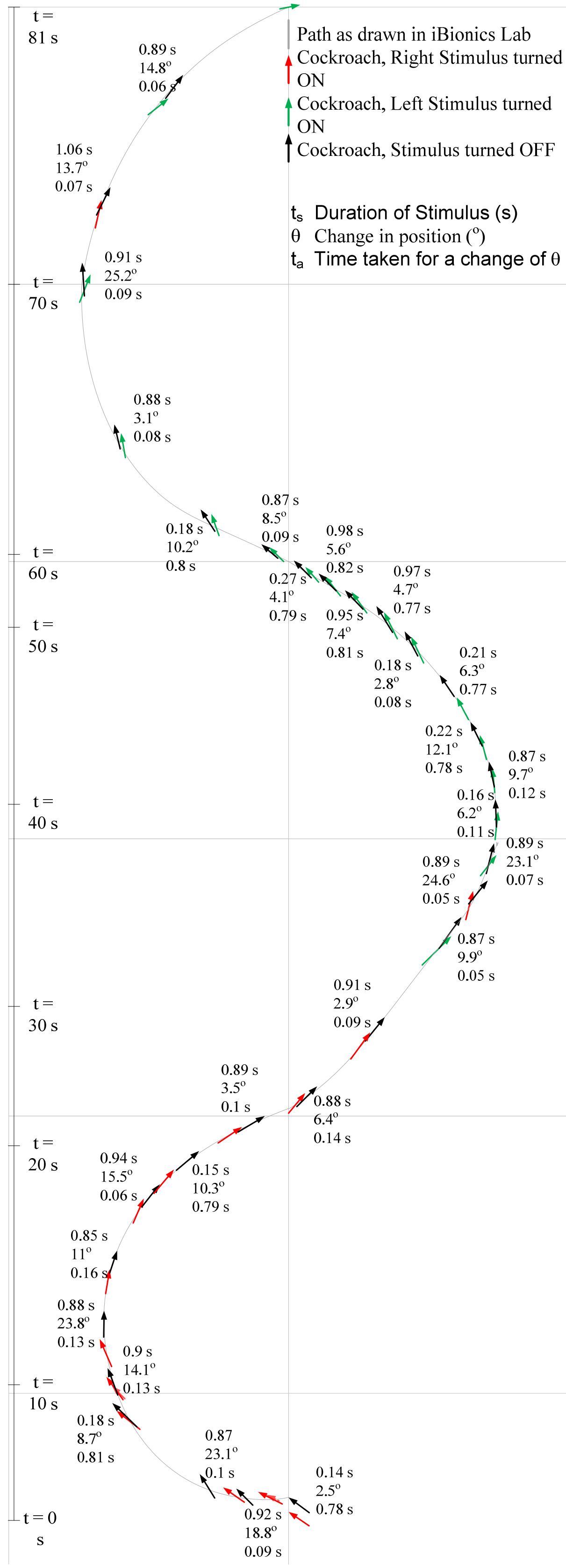

Figure 4: The typical response trajectory of the insect.

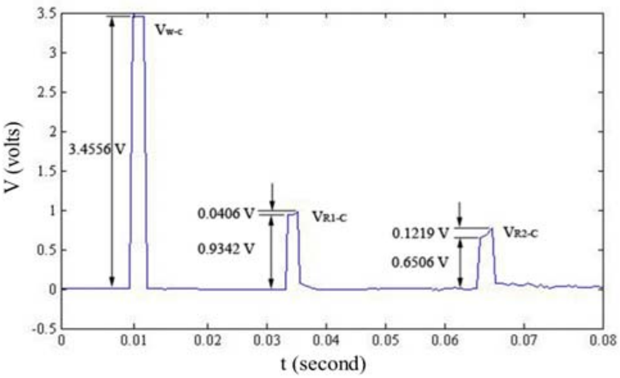

Figure 5: Assessment of the voltage across the tissue-electrode interface via the analysis of voltage excursions of V_{W-C}, V_{R1-C}, V_{R2-C}.

Despite the fact that hissing cockroaches have more than 5g of payload carrying capacity, we observed that the weight of the backpack adversely affected the stimulation outcome. Although, we have relatively higher success rate to obtain individual right and left turns, the success rate of completing the S-shaped lap in two-directions was around 10%, currently. The light-weight system, based on CC2530, is currently under experimentation where our initial results suggest an increase in the walking speed with the reduction of the payload.

To test our microcontroller based tissue-electrode coupling verification procedure, we carried out experiments with 0.09% saline solution. We applied a 3V square pulse between the working and counter electrodes while monitoring the voltage across the reference and counter electrodes. Then, we used this to predict the voltage across the electrode-electrolyte interface which should be below 0.7V to avoid evolution of oxygen. All three electrodes were stainless steel, insulated with Teflon with an opening at the tip. Analyses of the voltage excursions (Figure 5) resulted with a voltage drop of 0.68V across the working electrode-electrolyte interface and 0.37V voltage drop across the counter electrode- electrolyte interface, both of which was below the limits. Longevity of these measurements is currently under investigation. Our preliminary assessment suggests that this procedure can be used during neuromuscular stimulation to ensure an electrochemically safe operation.

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