Towards Fenceless Boundaries for Solar Powered Insect Biobots

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***Abstract*— Demonstration of remote navigation with instrumented insects, such as the Madagascar Hissing Cockroach, *Gromphadorhina portentosa,* has enabled the concept of biobotic agents for search and rescue missions and environmental monitoring applications. The biobots can form the nodes of a mobile sensor network to be established, for example, in unknown and dynamic environments after natural disasters to pinpoint surviving victims. We demonstrate here, for the first time, the concept of an invisible fence for insect biobots with an ultimate goal of keeping insect biobots within a certain distance of each other or a base station to ensure a reliable wireless network. For extended mission durations, this fenceless boundary would also be used to guide insects towards light sources for autonomous solar charging of their on-board batteries.**

I. INTRODUCTION

Insect biobots are "working" insects equipped with electronic backpacks containing wireless communication and remote navigational control circuits. "Biobotics" provide novel approaches to address issues where conventional and centimeter scale robotics may fall short. For example, the use of insects as biobots may prove to be a beneficial addition to search and rescue missions. With their highly efficient and stable locomotion capabilities, they could aid first responders after disaster scenarios by carrying small backpacks equipped with cameras or microphones. Moreover, swarms of biobots can form a mobile sensor network (Figure 1) to sweep an area to look for survivors inside a collapsed building or perform environmental sensing near an industrial plant. The gathered information can be relayed to remote base stations more efficiently through a mesh network where biobotic mobile sensor nodes are placed and maintained at desired locations.

Our foray into biobotics involves developing aerial biobots with hawkmoths, *Manduca Sexta,* and terrestrial biobots with hissing cockroaches, *Gromphadorhina portentosa* [1-12]. Electrical excitation of flight muscles, the antennal lobe, and neck muscles of the tethered or lift-assisted hawkmoths enables guided flight maneuvers [1-10], and stimulation of the antennae in hissing roaches allows controlled navigation through a designated path [11-12]. For an objective assessment of biobotic navigation capability, we also developed an automated system over-looking a flat test arena to detect and identify the terrestrial biobot and perform a predefined line following task [12]. In a step towards a more realistic environment, in this study, we erect walls in the test arena and establish a maze-based testing platform, where a successful biobot is guided from START to FINISH with minimum interference from its natural instinct to stay in shadowy regions and follow the wall corners.

The guided locomotion we have presented so far is beneficial for navigating a biobotic node from one location to another. To form a reliable sensor network, the biobots need to be maintained within each other's transmission/ reception area. The use of electronic invisible pet fences is a common practice to keep pets or livestock inside a marked territory [13]. In this study, we also demonstrate the possibility of maintaining the location of the insect biobot within a set of predefined boundaries without the use of physical barriers through the use of our Microsoft Kinect-based test platform [12, 14]. We define a fenceless boundary and use the ZigBee-enabled biobot backpack to provide wireless and automated neuro-stimulation pulses and guide the biobot back to the interior of the invisible fence. In parallel, we are also in the process of developing camera-free remote localization techniques [15]. Once achieved, the localization information can be used with the invisible fence to establish a reliable and autonomous mobile sensor network with the ZigBee-compliant biobotic nodes.

The electronic insect backpacks we presented before require disposable or rechargeable batteries for data acquisition, stimulation, and radio transmission [1-12]. The replacement or recharging of the batteries requires human intervention, thereby limiting the operation duration. To enable longer duration autonomous missions, in this study, we also added solar panels to the backpack where the invisible fence would be used to keep the insect under the sun or a nearby light source for automatic charging.

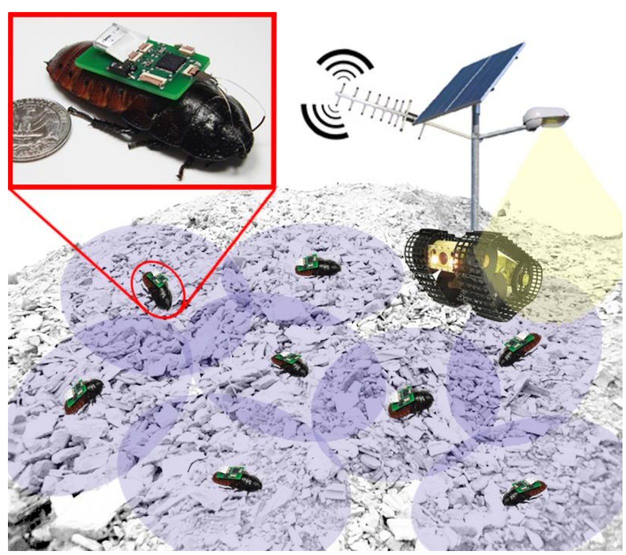

Figure 1. Artistic diagram describing biobotic sensor network searching a rubble pile. Only the biobotic agents at the surface are shown with solar powered mobile transceiver tower.

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II. Biobotic Control Experimental Setup and Results

A. Insect Biobot

The insect biobots for this study were enabled by surgical implantation of stimulation electrodes to the antennae of hissing cockroaches. The electrodes were PFA-insulated (thickness: 35 µm) stainless steel wires (diameter: 127 µm). Working electrodes were implanted to the flagellum and common electrodes to the thorax after anesthetization [11]. Surgical procedure was performed adhering to appropriate ethical standards [2, 16]. After a 24 h recuperation period, biobots were equipped with a TI CC2530 [17] system-on-chip based stimulation backpack powered by a single-cell 20 mAh lithium polymer (LiPo) battery (Figure 1). Experiments were carried out in the Microsoft Kinect-based evaluation platform [12] with a stimulation strategist that sends stimulation command to the backpack via a USB radio transmitter [18]. Upon receiving a command, the backpack delivers a stimulus to the antenna, causing the biobot to make a small turn in the appropriate direction.

B. Stimulation Profile

In our earlier studies [12], the position of the biobot in the arena was monitored every 500 ms and a stimulating pulse train was applied if necessary. To further characterize the performance, we tested a range of monitoring durations from 200 ms to 500 ms over a course of different experiments. These pulse trains contained pulses with 50% duty cycle and 30-50 ms width. We observed that shorter but more frequent turns enabled a smaller radius of curvature, which would be useful when precise control is needed.

C. Maze Navigation

To automatically test the navigational control over the hissing cockroaches, we used the Microsoft Kinect-based system and line-following task presented in [12]. The extension of those experiments is the maze navigation where vertical walls were erected in the test arena. Maze navigation introduces an additional complexity towards simulating real life scenarios where wall corners and shaded areas would be preferred by the insect during its natural locomotion and hinder the completion of the maze.

The experiment was carried out in an arena measuring 1×1 m^2 (Figure 2). Representative tests can be seen in [19]. Figure 2 shows the distribution of angular change in the desired direction in response to a stimulus during five different maze navigation experiments. The angular change is calculated by finding the difference in the angular position of the biobot between application of two consecutive stimulus. The mean angular change in the desired direction was found to be 1.5° with a median value of 1.48°, and skewness of 0.52, indicating an inclination towards positive skewness. Some of the individual responses were in the direction opposite to that desired due to the insects' natural wall-following instinct. However, most of the turns were in the desired direction. In contrast, line following experiment data from [12] shows a distribution with a mean change of 11.82°, median of 8.29°, and a skewness of 1.99 on a flat arena. This shows the decrease in the performance where the

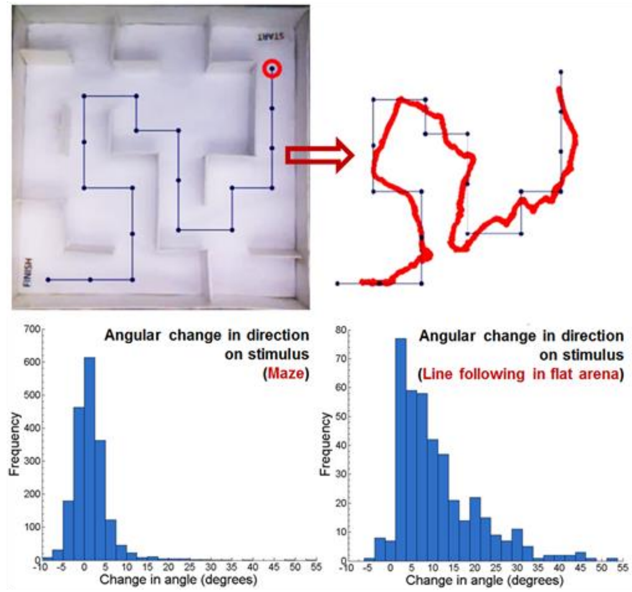

Figure 2. (Top Left) Maze Arena and (Top Right) overlay of path taken by a biobot on designated path. Histogram of angular change in desired direction in response to a stimulus, for (Bottom Right) line following [12] and for (Bottom Left) maze navigation.

obtained angular change is smaller when the insect is traveling in a narrower corridor. The shift towards the negative angles is likely a result of the presence of nearby walls.

D. Invisible or Virtual Fence

An invisible fence is a virtual boundary defined in software to keep a biobot inside a designated area. The biobot moves around freely and naturally while inside the invisible fence, but is navigated back inside if it exits the fence boundaries. Figure 3 shows the graphical user interface of the Kinect platform with predefined invisible fences during an experiment in progress. Zone 1 defines the threshold of the invisible fence and Zone 2 defines the safety margin boundary within which a biobot would take the necessary turns to go back inside Zone 1. Our aim is to minimize this safety margin as much as possible. Invisible fence experiments were carried out in an 1×1m^2 empty arena. As a starting point, the Zone 1 diameter was set as 35cm and Zone 2 was experimentally found to be satisfactory at 70cm diameter. Trials were deemed a failure when a biobot moved out of Zone 2 and did not return back to the fence. While further research on studying the failure modes is under way, it is noteworthy that the failed experiments often result out of a natural tendency of cockroaches to crawl walls. A total of 50 experiments were carried out on 8 biobots at different times of the day. The performance parameters considered were containment effectiveness (percentage of time a biobot was inside the fence during an experiment), and zone crossings (the number of time they were outside the fence). Each experiment, being of varying duration, was standardized by splitting into one minute chunks, and the corresponding parameters were evaluated accordingly. The rightly skewed nature of the histograms (Figure 3) suggests a positive outcome of the experimental hypothesis.

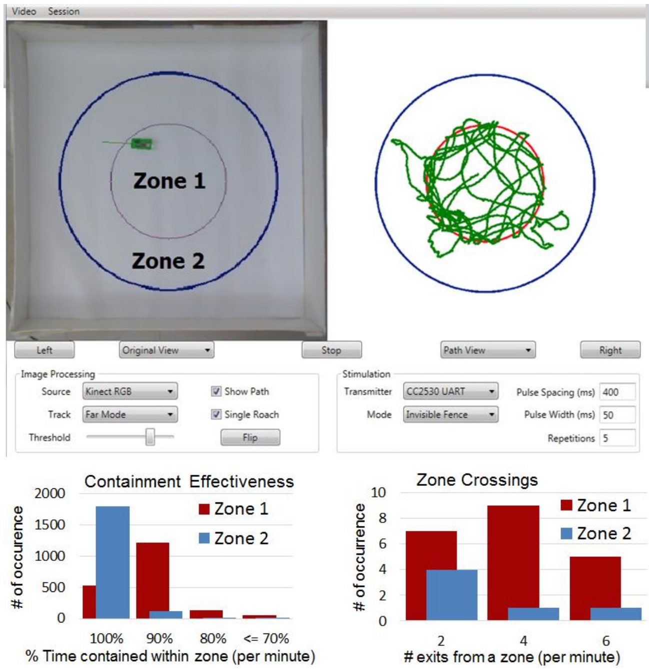

Figure 3. (Top) Graphical user interface of the invisible fence platform with an experiment in progress [20] shown. (Bottom) Performance parameters and histogram for invisible fence experiments.

E. *Ceasing Biobot Locomotion for Invisible Fence*

We observed that, in some biobots, simultaneous stimulation of both antennae (simultaneous right and left turn commands) simulated an obstacle directly in front of it and halted the insect briefly for around 0.5 s to 1 s before it continued to move in a forward direction [21]. Shorter pulse widths in the range of 10 ms to 50 ms resulted in a better stopping behavior success rate, while increasing the pulse width caused a longer stopping duration before the insect resumed moving. This could provide an alternative approach to prevent biobots from leaving the periphery of an invisible fence. However, when the brief pulse application is over, the insect continues to move in the forward direction. Therefore, continuous pulsing is required to achieve an invisible fence, thereby inducing the risk of accumulating charges at the tissue electrode interface and saturating it.

For the presented results so far, monophasic voltage pulses were applied to the tissue for stimulation, as it is relatively easier to generate voltage waveforms and minimize the backpack board size. Biphasic current stimulation would provide an improved and more reliable angular control. To achieve this, we have connected voltage controlled biphasic current sources (+/- 0.5 µA) between the voltage output channels and the electrodes where the switching command is synched with the stimulus. The invisible fence experiments with this improved system are still in progress.

III. Solar Power Based Self-charging Circuit

A new improvement to the biobot backpack is the addition of a solar-based self-charging circuitry to power the backpack, and charge up the LiPo battery when required. This self-charging operation has been enabled by the invisible fence where the insect can be brought and maintained near a light source to charge up the batteries. Most cockroaches rest during the day time and are more active during the night. Therefore, the day time sunlight or a nearby light source during night time (Figure 1) can be used to directly power the backpack or charge up the batteries.

A. *Circuit Operation*

The charge management controller circuit shown in Figure 4 scavenges energy from a high-efficiency mono-crystalline solar cell and stores it in a single-cell LiPo battery. The circuit uses an MCP73871 charge management IC [22] employing voltage proportional current control (VPCC) to keep the solar panel near its maximum power output. The reference point for the VPCC circuit is set to 91% of the maximum supply voltage, or 4.55 V for a 5 V source, which makes it useful for very low-power solar cells. The circuit charges a battery until 4.2 V is reached; it then switches to constant voltage mode. Integrated load sharing and a low battery indicator allow the circuit to power a load while scavenging solar energy.

B. *Performance Testing*

The solar panel comes in two sizes (Figure 4). During the testing, the larger panel was used where a maximum power output of 223 mW was achieved [23]. The solar panel was placed under various light sources to monitor the power generated to charge the battery from 3.2 volts to 4.2 volts, during which the battery voltage was recorded at a sampling rate of 0.1 Hz and the total time required to reach 4.2 volts was measured (Figure 5). The increase in the temperature on the surface of the solar cell was also recorded using a thermocouple. The incandescent light bulb was tested at three different distances from the solar panel. Indirect sunlight refers to some partial cloud cover and a rotation of the solar panel away from the sun. The tested light emitting diode (LED) sources were a 250 lumen focused white LED package, and an array of unfocused red LEDs. A 20 mAh battery can be charged in under 2 hours in both direct and indirect sun, under a focused white LED, and under an incandescent bulb at a distance of 8 centimeters. Since the cockroaches are inactive and rest for ~8 h per day, it is possible to fully charge the battery during those inactive periods, which could allow for continuous experimentation over long periods of time. The invisible fence can be used if charging is required during the active periods.

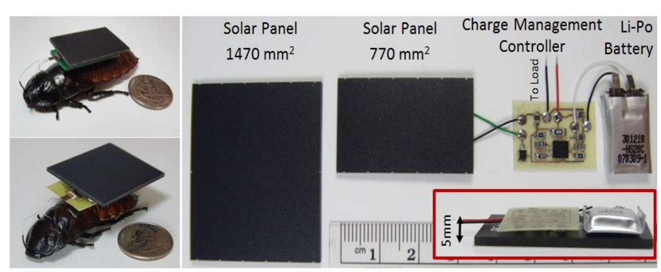

Figure 4. (Top Right) Charge management circuit, (Bottom Right) compact system is small and versatile, (Left) system mounted on biobots.

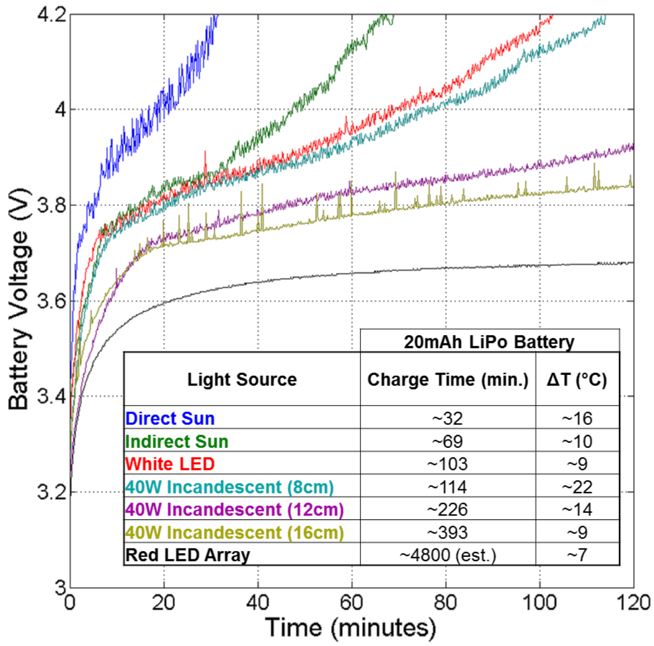

Figure 5. Charging profile of 20 mAh LiPo battery under varying light sources. (Inset) Time and temperature increase above ambient due to light source for the 20 mAh battery.

IV. Conclusion

The biobotic control of insects has enabled a novel cyber-physical approach where the natural locomotion capabilities of insects have been proposed to carry sensors in unknown and dynamic environments to establish a distributed mobile sensor network. We have earlier demonstrated an automated platform using a Kinect to objectively characterize the biobotic capabilities of instrumented hissing cockroaches in a flat test arena. In this study, we present the addition of a maze task to this platform to further characterize the biobotic navigation capabilities. We have also demonstrated a fenceless virtual boundary (invisible fence) toward establishing a sensor network where biobotic agents can be maintained within each other's reception area. In addition to improving the wireless connection reliability, such an invisible fence can also be used for solar or light-based charging of the batteries powering biobots electronic backpacks.

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