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DIRECTED LOCOMOTION IN COCKROACHES: "BIOBOTS"

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Abstract - We have been able to steer 10-20% of the Madagascan hissing cockroaches *(Gromphadorhina portentosa)* tested with minimally invasive low-power electrical stimuli to the basal regions of either their antennae or cerci, directing them to follow prescribed courses and even to collect "samples" and return them to the point of origin. Some of the demonstrations have been documented videographically, and the efficacy of the techniques has been established by repetition in other laboratories by William Schwind, University of Michigan, and by Prof. I. Shimoyama, University of Tokyo, Japan. Our demonstration establishes the capability of using the locomotor power of these living "robots" (biobots) to carry existing experimental sensory and communicative devices to and from areas difficult or dangerous for human activity. Further prospects for eliminating tethering stimulus-wire cables, and satellite radio communications from any location in the world, may open unparalleled opportunities for monitoring natural phenomena, including synchronized neural, muscular, and skeletal interactions during untethered behavior in nature.

Izvleček - NADZOROVANO GIBANJE ŠČURKOV: "BIOBOTI"

S šibkimi električnimi dražljaji v bazalne dele tipalnic ali cerkov smo uspeli usmerjati 10-20% madagaskarskih sikajočih ščurkov *(Gromphadorhina portentosa)*. Vodili smo jih po predpisanih poteh in celo dosegli, da so pobrali vzorce in jih vrnili na začetno točko. Nekaj poskusov smo posneli z video kamero, uspešnost postopkov pa so s ponovitvijo poskusov v svojih laboratorijih potrdili William Schwind z Michiganske univerze in prof. I. Shimoyama s Tokijske univerze na Japonskem. Naši poskusi potrjujejo možnost uporabe gibalnih sposobnosti živih "robotov" (biobotov) za prenašanje obstoječih poskusnih naprav za zaznavanje in komunikacijo po območjih, nedostopnih ali nevarnih za ljudi. Pričakovana odstranitev veznih žic za prenos dražljajev in komunikacija s pomočjo radijskih valov prek satelita s katerekoli točke na svetu odpirata enkratne možnosti spremljanja naravnih pojavov, vključno z usklajenim delovanjem živčevja, mišic in skeleta med prostim gibanjem v naravi.

Introduction

There is an increasing appreciation of the structural and operational properties of insects and other arthropods as models in relation to robotics and other engineering applications (Beer et al. 1993, Loudon 1995, Zill and Seyfarth 1996, Donahue 1996, Anonymous 1997, Holzer and Shimoyama 1997). Micro-electromechanical systems engineering (MEMS) has opened an expanding arena of sensors and stimulators that has spurred interest in microrobotics. Many have modeled grossly arthropod-like multi-legged robots, with varying success in locomotion (Zill and Seyfarth 1996). All reported attempts have been seriously limited in duration and distance by power source, and in locomotor ability in complex terrain.

Our approach has been to simply test the prospects for steering a living insect capable of carrying a small sensory and communication backpack (Fig. 1), thus harnessing its energy and remarkable full locomotor capacity and requiring battery energy only for sensory and communication devices carried on its back, potentially creating what we coined a "biobot" in 1992 (Koditschek et al. 1993). We chose Madagascan hissing cockroaches [Blattaria, Blaberidae, *Gromphadorhina portentosa* (Schaum)] for our preliminary tests because they are large, strong, easily reared in the laboratory, sufficiently slow-moving for ready evaluation of responses to stop, start, and steering commands, and have no wings or other impediments on their backs as adults that would get in the way or would have to be removed. Steering control of 4.5-5 cm adults was accomplished by means of a 1.5-2.0 m micro-cable of either three or five 38 gauge copper stimulus wires connected from a control box through a micro-connector attached to the back of the roach, and similar fine stimulus wires from the micro-connector inserted mid-dorsally in the abdominal cavity and into the body cavity either at the antennal bases or also at the cercal bases. A wrist-watch-size 16-microsensor package with data storage and compatible micro-radio for two-way communication were independently developed during the time this work on cockroaches was conducted, and exist as laboratory devices at the University of Michigan. They are available, but have not yet been attached to the roaches or tested in outdoor applications. We do know that the roaches can carry more than the physical load of these combined instruments. A sufficiently miniaturized stimulus package has not yet been designed for coupling with these sensory and communication devices to allow for steering without cable connections, basically similar to the technique demonstrated by Kutsch et al. (1993) in recording muscle potentials during free flight in locusts.

Materials and Methods

The materials for these experiments included a portable source of stimulating current and cables that delivered the current to the animal's body (Conklin et al. 1994, Crary et al. 1996). The source was a custom built battery powered square wave generator, unipolar, with four output channels, a common or indifferent connection, and manual controls for adjusting output signal properties. The manual controls included selectors for choosing one of six current magnitudes (respectively: 170, 120, 90, 71, 62, and 54 microamperes), one of six possible signal frequencies (respectively: 40, 50, 60, 70, 87, 105 Hz), and one of five signal duty cycle settings (repetition respectively: 5, 8, 11, 16, 21 Hz, with equal on and off intervals), along with toggle switches for directing the output signal to one or more of the four alternative output channels (left or right antennal base; left or right cercal base). No consistent single effective combination of stimulus patterns was identified. Different animals responded best to differing combinations, and parameters commonly had to be varied during testing a single animal in order to sustain responses.

Cables from the source were connected to a Samtec™ 7-pin "backpack" attached with beeswax to the animal's back (Fig. 2). The backpack leads were soldered to stimulus wires (38 gauge copper wire) that were surgically implanted in either three or five locations. The common or indifferent lead was inserted between exoskeletal plates on the animal's back. Stimulus wires were inserted ventrolaterally into the head capsule cavity through the softer basal articulating skeleton of the animal's antennae, connecting one lead to the base of each antenna, and also sometimes were inserted similarly into the body cavity through the softer articulating skeleton at the base of the animal's cerci, and again one lead was connected at each. Thus, a maximum of four active leads were inserted with rough bilateral symmetry at the animal's anterior and posterior; their internal locations were not marked or stained. The copper wire was tinned with solder on the end inserted less than 2 mm into the animal's body cavity, in an attempt to reduce copper/blood interactions such as phenyloxidase reactions producing melanins. The chronic clip electrode technique for recording neural activity from cervical connectives may suggest a better way to avoid melanin deposition during prolonged periods of stimulation (Ye and Comer 1996).

Results

The response of the animals to this stimulus was extremely varied. In almost all cases, higher current resulted in more obvious "startle" or "cringing" behavior. In some cases, there was very little other observed response to stimulus of any kind (cf Huber 1984). In many cases, current directed to the left antenna would result in a right turn and current directed to the right antenna would result in a left turn. In most cases, current directed to the base of the cerci resulted in faster forward motion, while current similarly directed to the antennae resulted in slowed walking, halting, or, sometimes, even reverse motion. The kinds of afferent receptor (neural) fibers likely influenced by our stimuli can be catalogued from the works of Schneider (1964), Gnatzy and Hustert

(1989), Rozhkova et al. (1990), Mizunami et al. (1993), Burdohan and Comer (1996), and Ye and Comer (1996). Stimulating simultaneously at the base of one or both antennae and of one or both cerci consistently resulted in the roach raising its midsection away from the ground and remaining otherwise motionless. In all cases, we witnessed a progressive decrease in response ending in a "refractory" period during which there was almost no observed response to any stimulus.

Decrease in response seems to be associated both with a melanic residue accumulating on the wire leads, presumably from a phenyloxidase reaction, as well as a systemic habituation to the stimulus. Melanic residue was consistently generated on live wires immersed in vitro in the insect's blood. We suspect that a charge balanced signal would reduce this effect. Systemic habituation was clearly present: stimulating an animal previously subjected to numerous stimuli, at a fresh site with a fresh lead, elicited far less response than did the initial stimuli. The onset of the refractory period varied greatly in different animals, ranging from the twentieth through the two hundredth stimulus. Recovery to near full response was exhibited by animals that had not been tested for two weeks, although these generally exhibited a faster transition to the refractory period than during their first round of testing.

A small fraction of animals tested exhibited a sufficiently consistent highly sensitive and enduring response to our stimuli to convince us that further exploration of this phenomenon may lead to scientifically informative and potentially useful results. An example of this potentially useful range of animal responses to our procedure is provided by our experience in making a video record of one of our "path following" experiments (Pobojewski 1997). A zig-zagging "track" about 3.3 meters in length was laid out on the floor using black tape (Fig. 3), and one cockroach was released at a time at the beginning of the track with a long cable connecting its backpack to the signal source. To make this video, we tested fifty cockroaches, of which ten exhibited a consistent response to our stimuli and three exhibited a sufficiently enduring response to carry out the following "commanded maneuvers." One of us (Conklin) systematically applied current at the base of the cerci to stimulate forward movement, and to one or the other side (base of antenna and/or contralateral cercus) when the animal strayed off the tape path. The responsive animals were successfully "driven" around the track in this fashion, as our video footage documents. Subsequent successful steering trials were achieved while stimulating similarly through the basal articulating skeleton of only antennae. We also were able to document videographically similarly guided animals, dragging 10 cm behind themselves a 10.5 cm thin cardboard strip attached dorsally to their abdomens by dental floss and beeswax, that were steered to climb a 9 x 25 cm incline, then through one to three 3 x 5 cm rectangular thin cardboard hoops weakly fixed to the substrate with sticky wax, and then to return along the track with the collected hoops ("samples") to the point of origin.

Discussion

We have demonstrated that it is possible to harness the power of a living cockroach to carry a burden equivalent to a wristwatch-size sensory and communication package and to collect objects which could be samples from nature, and to steer them to and from specified locations. Such communication packages delivered by untethered insects could make possible remote measurements of environmental conditions where the animals live, or where humans could not easily or safely go, including external or internal environmental conditions of the insects themselves, such as simultaneous muscle or nerve contraction patterns or activity periods, skeletal strain data, etc. This sort of data might also be used to analyze complex behavior patterns such as walking and running in nature. Similar packages might well be used in gathering data to model mathematically the properties of cockroach gait control and to make predictions about the nature of connectivity and functioning of their relatively simple neuromuscular networks. The recent work of Holzer and Shimoyama (1997) reports results similar to ours, and suggests similar prospects based on computerized trackball tests using tethered American cockroaches [*Periplaneta americana* (L.)] with very different stimulus parameters applied to antennal stumps. Results of work also on American cockroaches by Comer and Dowd (1993), Liebenthal et al. (1994), Ye et al. (1995), Burdohan and Comer (1996), and Ye and Comer (1996) more precisely describe neural pathways and stimuli that may be involved in control of turning in cockroaches (several thousand species) in general.

These successes presage a new paradigm in robotics derived from a novel blending of biology and micro-electromechanical systems (MEMS) engineering analogous to but distinct from the conjunction of neurobiology and computer science. Advances in device electronics and packaging promise to bring to biomechanical and behavioral studies of free-ranging animals a sophisticated level of instrumentation at least equal to that heretofore reserved for prepared specimens. Just as the dramatic advances in neurobiological science have both influenced and benefited from the design of advanced computational architectures, it seems clear that a systems level integrated view of autonomous physically situated mechanisms (a view common to animal behavior and robotics) may now tie these disciplines together in new ways that dramatically advance both. The available sensory and communication devices at the University of Michigan have yet to be tested on the backs of these animals, and in nature. Potentially, linked with nearby more powerful radio equipment with longer-lasting power sources, such monitoring episodes could take place in any number of replicates over long periods of time anywhere in the world, and could be received anywhere else in the world through satellite communications. Such models of interaction between engineering and biology have recently come to enjoy government sponsorship in the United States and several other countries. Systematic and more precise exploration of steering stimuli and protocols, and of integrated computer backpack and iridium/silicon stimulus probe circuitry, in relation to gait stabilization, is currently underway in our laboratories.

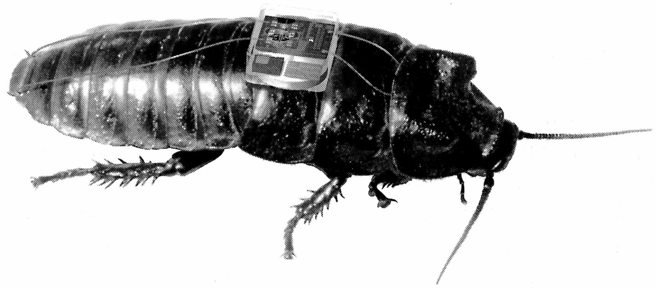

Fig. 1: Artist's rendering of backpack and stimulus wire configuration envisioned for Madagascan cockroach biobot.

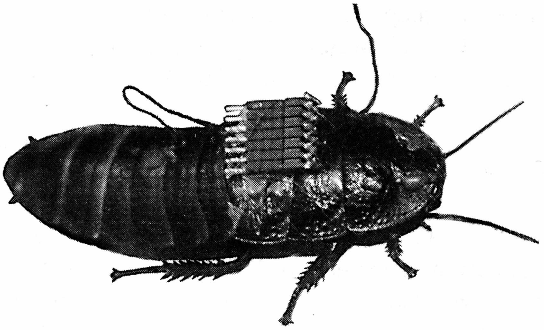

Fig. 2: Retouched photograph (background made uniform) of a Madagascan cockroach being steered on the path mentioned in the text, during a televized recording for a Cable News Network, CNN Daybreak Saturday, news brief (March 29, 1997); cable connecting to the control box extends upward in front of the connector.

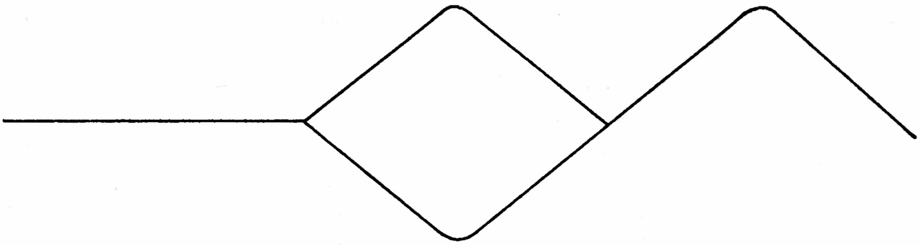

Fig. 3: Diagram of maze of 19 mm wide black electrical tape on laboratory floor; each central segment ca. 58 cm to center of bend, straight end segment ca. 95 cm, angled end segments ca. 55 (closest to center) and 64 cm.

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