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Insect-Machine Hybrid System

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Abstract— **We demonstrated the remote control of insects in free flight via an implantable radio-equipped miniature neural stimulating system. This paper summarizes these results. The pronotum mounted system consisted of neural stimulators, muscular stimulators, a radio transceiver-equipped microcontroller and a microbattery. Flight initiation, cessation and elevation control were accomplished through neural stimulus of the brain which elicited, suppressed or modulated wing oscillation. Turns were triggered through the direct muscular stimulus of either of the basalar muscles. We characterized the response times, success rates, and free-flight trajectories elicited by our neural control systems in remotely-controlled beetles. We believe this type of technology will open the door to in-flight perturbation and recording of insect flight responses.**

INTRODUCTION

Micro and nano air vehicles (MAV's / NAV's) — defined as aircraft with total mass less than 100 g and wingspans less than 15 cm [1-4] — are the subject of intense research and development. Despite major advances, M/NAV's still present significant trade-offs between payload mass, flight range, and speed. Currently, the principal limiting factors are the energy and power density of existing fuel sources and the complexity of flight dynamics in very small flyers. Insects have flight performance (as measured by distance and speed vs. payload and maneuverability) unmatched by man-made craft of similar size. Moreover, both the flight dynamics and the neurophysiology of insects are increasingly well understood [5-15].

In biology, the ability to control insect flight would be useful for studies of insect communication, mating behavior and flight energetics, and for studying the foraging behavior of insect predators such as birds, as has been done with terrestrial robots [16]. In engineering, electronically-controllable insects could be useful models for insect-mimicing M/NAV's [17-19]. Furthermore, tetherless, electrically-controllable insects themselves could be used as M/NAV's and serve as couriers to locations not easily accessible to humans or terrestrial robots.

Flight control of insects ideally requires the triggering of flight initiation and cessation as well as the free-flight adjustment of orientation with three degrees of freedom [8]. These flight parameters are controlled by insects via modulation of the wing movements using flight muscles. Insects exhibit two major categories of flight muscular control [9]. Some insects, such as dragonflies and locusts, possess synchronous flight muscles which oscillate under direct flight control with one-to-one matches between neuronal stimulus episodes and wing muscle contractions. Other species (e.g. Hymenoptera, Diptera, Coleoptera), possess asynchronous flight muscles which oscillate under indirect control. In these species, motor neurons to the flight muscles fire at much lower frequencies than the wing oscillation frequencies, and neuronal output serves to turn flight on and off, and to modulate power, but not to directly control each flight muscle contraction [10-12].

Beetles (Coleoptera) include some of the largest of all insect species and thus have relatively high potential for load carriage; we chose *Cotinis texana* (ca. 2 cm, 1 g) and *Mecynorhina torquata* (ca. 6 cm, 8 g) because they were large enough to carry the microsystem presented here, and could be easily reared in the lab (both species were capable of flying with 20 – 30% body weight)

We chose to attempt to start, stop and modulate wing oscillations using direct electrical stimulus of the brain. Turns require asymmetric output from wing muscles [15]. We attempted control of turns by asymmetric electrical stimulus of the basalar muscles, one of the major indirect flight muscles of these beetles [11, 12, 20].

EXPERIMENT

The remote control system used two microcontrollers (6 x 6 mm, 130 mg, 2.4 GHz); one acting as the beetle-mounted RF receiver and one as the computer-driven RF transmitter base station. We manufactured custom PCB's (16 x 13 mm, 500 mg) for the receiver. A programmed microcontroller was mounted on the PCB as shown in Fig. 1. The microcontroller was powered by a rechargeable micro lithium-polymer-battery (Micro Avionics, 4 V, 8.5 mAh, 350 mg). We employed Mecynorhina torquata beetle (ca. 10 g, 7 cm, 3.0 gram payload capacity) as the insect platform. The assembly was mounted on the beetle's posterior pronotum (Fig. 1) and glued with beeswax. The terminals of 6 output wires from the assembly were inserted into the left and right optic lobes, brain, posterior pronotum, left and right basalar flight muscles (Fig. 2).

RESULTS AND DISCUSSION

In Cotinis texana, alternating positive and negative potential pulses between an electrode implanted into the brain and a counter electrode implanted into the posterior pronotum of the adult insect reproducibly generated flight initiation and cessation in fully-tethered and weakly-tethered Cotinis beetles. For each insect there was a voltage threshold for flight initiation. Below this voltage, legs stretched or contracted but flight did not start.

During flight, body pitch and wing oscillation frequency could be manipulated by modulating the wing oscillations with the neural stimulator. For Cotinis texana, we observed that progressively shortening the time between positive and negative pulses led to a 'throttling' of flight where the beetle's normal 76 Hz wing oscillation was strongly modulated by the 0.1 – 10 Hz applied stimulus.

Given the initial data from Cotinis, we chose to extend this study to control of beetles in free flight; this required a slightly larger beetle to carry our radio-equipped system (RF receiver + battery = 1.3 g). As with Cotinis, we first determined the optimal stimulation potential amplitude required to start and stop flight in tethered Mecynorhina torquata. During these experiments we also found that the application of these potential pulses between electrodes implanted at the interior base of the left and right optic lobes yielded a much higher success rate as compared to the method used with Cotinis and, unexpectedly, did not affect the beetle's ability to steer in free flight. Given this data, we were then able to repeatably trigger flight initiation and cessation in unthethered, free flying insects. Once flight was initiated, it tended to persist without additional stimulation for both tethered and free-flying beetles. A single pulse applied between optic lobes stopped flight for Mecynorhina torquata. Multiple flight initiation and cessation rounds were possible for most beetles tested and there was no evidence of impaired flight ability after 30 – 60 mins of tests (set by the lifetime of the battery). Moreover, beetles were repeatedly flown on subsequent days, demonstrating that the stimulation resulted in little permanent damage.

For Mecynorhina torquata, brain stimulus at 100 Hz in the same manner as Cotinis texana led to depression of flight. Set on a custom pitching gimbal, Mecynorhina torquata could be repeatedly made to lower its attack angle to the horizon when stimulated. In free flight, this corresponded to a controllable drop in altitude when stimulated. One second of stimulus resulted in a 60 cm median drop in altitude.

Turns were elicited by stimulus of the left and right basalar muscles with positive potential pulse trains. In Cotinis texana, the basalar muscles normally contract and extend at 76 Hz when they are stimulated by ~ 8 Hz neural impulses from the beetle nervous system [11, 12]. During flight, a turn was triggered by applying 2.0 V, 100 Hz positive potential pulse trains to the basalar muscle opposite to the intended turn. A right turn, for example, was triggered by stimulating the left basalar muscle. In free-flying Mecynorhina torquata, turns were elicited in the same manner but at 1.3 V. The success rates for left and right turns were 78 % (N = 42) and 66 % (N = 68), respectively. One second of stimulation to the left and right basalar muscles of free-flying beetles resulted in a 1.7° and -9.0° median roll, respectively, and 20.0° and 32.4° median banking, respectively; ten left and right turn trajectories are shown in Figure 4. During flight, beetles tended to adjust their attitude so as to fly parallel to the ground plane. This intrinsic characteristic of beetle flight made it possible to elicit turns in a desired direction with just one degree of control.

CONCLUSION

Our results demonstrate that it is possible to reliably control flight initiation and cessation and modulate flight throttle and direction with a relatively simple interface. To our knowledge, this is one of the first reports of reliable, tetherless neuro-stimulated flight control of insects.

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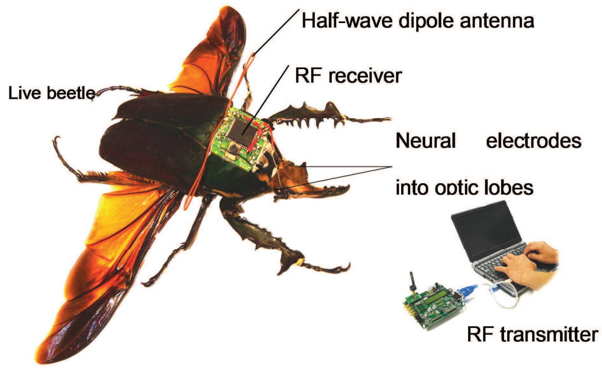

Figure 1: Radio-controlled live beetle.

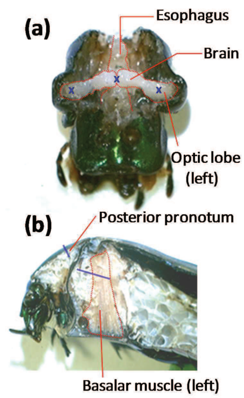

Figure 2: (a) front view of dissected beetle head showing the brain and optic lobe implant sites. (b) sagittal section of thorax showing the posterior pronotum implant, the basalar muscle implant (muscular stimulator). Cotinis texana (which has nearly identical, scaled anatomy to the Mecynorhina beetle) was used for these anatomical images.

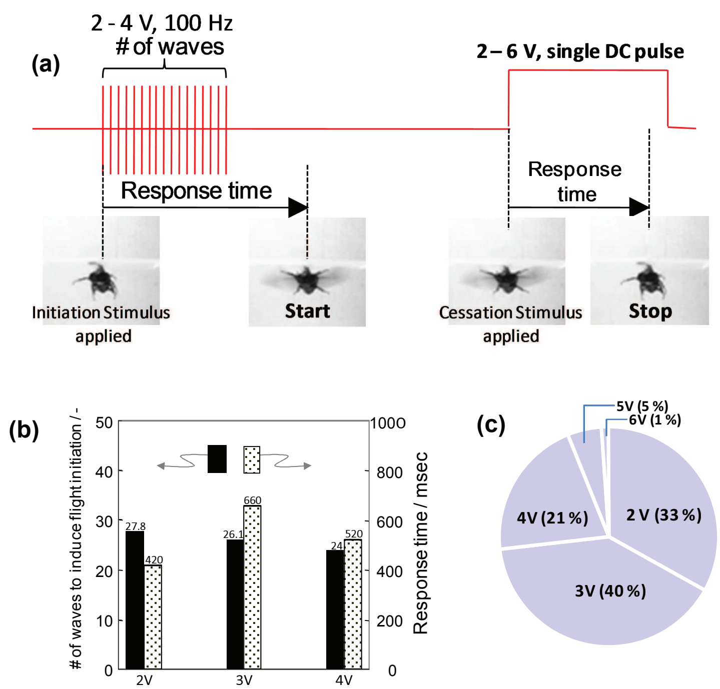

Figure 3: Flight initiation and cessation test. (a) alternating positive and negative pulses to optic lobes evoked beetle flight while a single DC pulse stopped the flight. All the tested beetles were successfully induced to fly by less than 100 waves and 4 V stimulus level. Success rates of flight initiation at different stimulus level were 90 % at 2V, 100 % at 3 V, and 100 % at 4 V. Average number of waves required and response time for flight initiation are shown in (b). For the cessation test, 2 V DC pulse (1 sec) was first applied, and then, the amplitude was increased by 1 V if the beetle did not stop flight within 1 sec. (c) shows the percentage of stimulus level required to stop flight (N = 100).

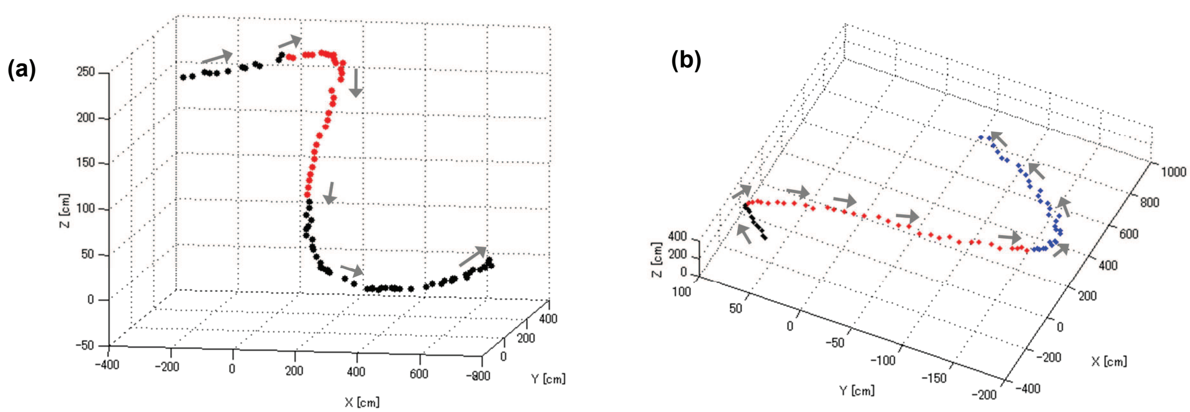

Figure 4: Representative flight paths of free-flying beetle stimulated for (a) turn control and (b) elevation control. These trajectories were plotted through frame-by-frame 3-D analysis of beetle flight movies recorded by 6 cameras located at different positions. The software used for the analysis was from the Hedrick lab [7]. Each dot on the flight path is corresponding to each frame of movie (30 frames per second). The black dots indicate unstimulated periods. The red and blue dots in (a) indicate stimulus of the left and right basalar flight muscles, respectively. The red dots in (b) indicate stimulus of brain.

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