RADIO-CONTROLLED CYBORG BEETLES: A RADIO-FREQUENCY SYSTEM FOR INSECT NEURAL FLIGHT CONTROL

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ABSTRACT

We present the first report of radio control of a cyborg beetle in free-flight. The microsystem (Figs. 1, 2) consisted of a radio-frequency receiver assembly, a micro battery and a live giant flower beetle platform (*Mecynorhina polyphemus* or *Mecynorhina torquata*). The assembly had six electrode stimulators implanted into the left and right optic lobes, brain, posterior pronotum (counter electrode), right and left basalar flight muscles. Initiation and cessation of flight were accomplished by optic lobe stimulation while muscular stimulation of either right or left basalar flight muscles (referenced to the posterior pronotum electrode) elicited left or right turns, respectively. Flight commands were wirelessly transferred to the beetle-mounted system (running BeetleBrain v1.0 code) via an RF transmitter operated by a laptop running custom software (BeetleCommander v1.0) through a USB/Serial interface.

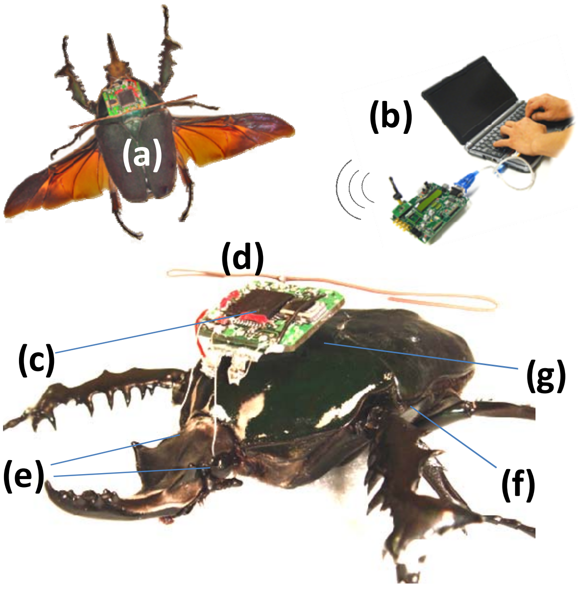

Figure 1: Photographs of a radio-controlled cyborg Mecynorhina beetle; (a) live beetle platform (Mecynorhina, 4 - 10 g, 4 - 8 cm), (b) RF transmitter (CC2431 microcontroller mounted on a Chipcon Texas Instruments SmartRF 04EB) operated by user's personal computer via USB/Serial-interface. (c) RF receiver assembly (Chipcon Texas Instruments CC2431, 2.4 GHz, on custom PCB, see also Fig. 2), (d) half-wave dipole antenna, (e) stimulating electrode terminals at both optic lobes, (f) basalar flight muscle (left), (g) posterior pronotum (counter electrode).

1. INTRODUCTION

Micro air vehicles (MAV's) which can navigate into locations not easily accessible to humans have been the subject of much recent research [1]. However, man-made MAV's are still limited in size, payload, distance and performance. In contrast, many insects have as-yet unmatched flight performance and increasingly understood muscular and nervous systems [2]. Additionally, some insects undergo complete metamorphosis (*i.e.* form pupae) and are amenable to implantation and internal manipulation during pupation. In light of this, there have been recent efforts by several groups to implant microsystems into insects to control their flight [3-8].

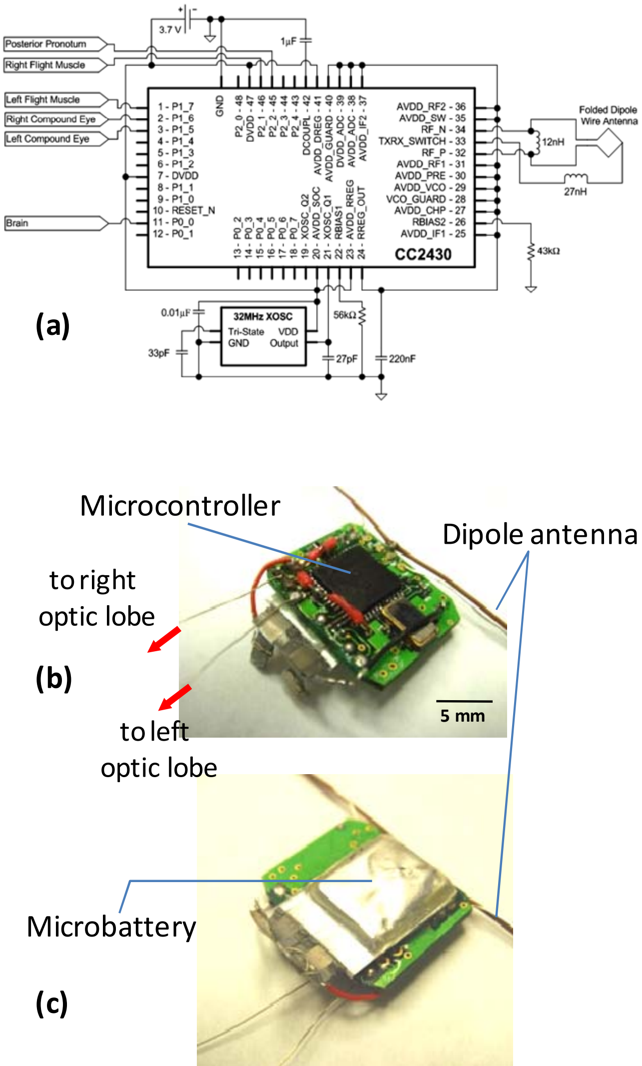

Figure 2: RF receiver assembly (a) circuit diagram, (b) front and (c) backside photographs. Total weight was 1331 mg; rigid PCB + misc components = 687 mg, microbattery (8.5 mAh, Micro Avionics) = 350 mg, antenna = 74 mg, microcontroller = 130 mg, insect adhesive = 90 mg.

If it were possible to remotely control the flight of insects, and receive information from on-board sensors, there would be many applications. 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 [9]. In engineering, electronically-controllable insects could be useful models for insect-mimicing M/NAV's [10-12]. 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.

We previously reported flight control of live beetles including initiation, cessation, elevation and turns using a conventional neural wire stimulators driven by a pre-programmed microcontroller, powered by a microbattery, mounted on the anterior pronotum [6, 7].

In this study, we extended this concept to include a microcontroller with an RF transceiver, an antenna and a slightly bigger microbattery. This allowed us to wirelessly remote control insect flight initiation, cessation and turning in free flight.

2. EXPERIMENTAL RESULTS

RF System

The remote control system used two Chipcon Texas Instruments CC2431 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. Based on the circuit diagram shown in Fig. 2(a), we designed and manufactured custom PCB's (printed circuit boards, 16 x 13 mm, FR4 (rigid) version: 500 mg, polyimide (flexible) version: 70 mg) for the receiver. After programming, the microcontroller and the other components were assembled on the PCB as shown in Fig. 2(b). The microcontroller was powered by a rechargeable micro lithium-polymer-battery (Micro Avionics, 4 V, 8.5 mAh, 350 mg) which was attached on the backside of PCB with a piece of double adhesive tape as shown in Fig. 2(c) and electrically connected to the PCB when used.

We employed *Mecynorhina polyphemus or Mecynorhina torquata* beetle (4 – 10 g, 4 – 8 cm) 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. 3).

Flight commands were generated by custom control software (BeetleCommander v1.0) running on a personal computer interfaced via a USB port with the transmitter (CC2431 microcontroller mounted on a Chipcon Texas Instruments SmartRF 04EB). BeetleCommander v1.0 allowed for in-flight control of stimulation parameters including frequency, number and duty cycle of control voltage pulses to stimulated sites. Signals were transmitted using the CC2431's built-in 2.4 GHz IEEE 802.15.4 compliant transmitter broadcasting on a single channel (1A, 2.480 GHz) using direct sequence spread spectrum RF modulation. The transmitter sent a command to the receiver every 1 ms for 300 ms when instructed to do so. The flight commands were mapped to appropriate voltage pulse trains at the beetle's neural stimulators by custom signal generating software (BeetleBrain v1.0) running on the receiver. To adjust the applied potential to a value other than the 4 V supplied from the lithium-polymer battery, surface mount resistors were soldered in parallel as voltage dividers to each output pin.

The working range of the beetle-mounted wireless system was ~10 m indoors in a modern office environment; outside, the range is 2 – 5 x greater depending on line of sight and objects present. At full power, the receiver consumes ~77 mW. Cycling sleep and receive modes, consumption is 10.95 mW for operation. The optic lobe and basalar flight muscle stimulations consumed ~500 µW and ~20 µW, respectively as shown in Fig. 4.

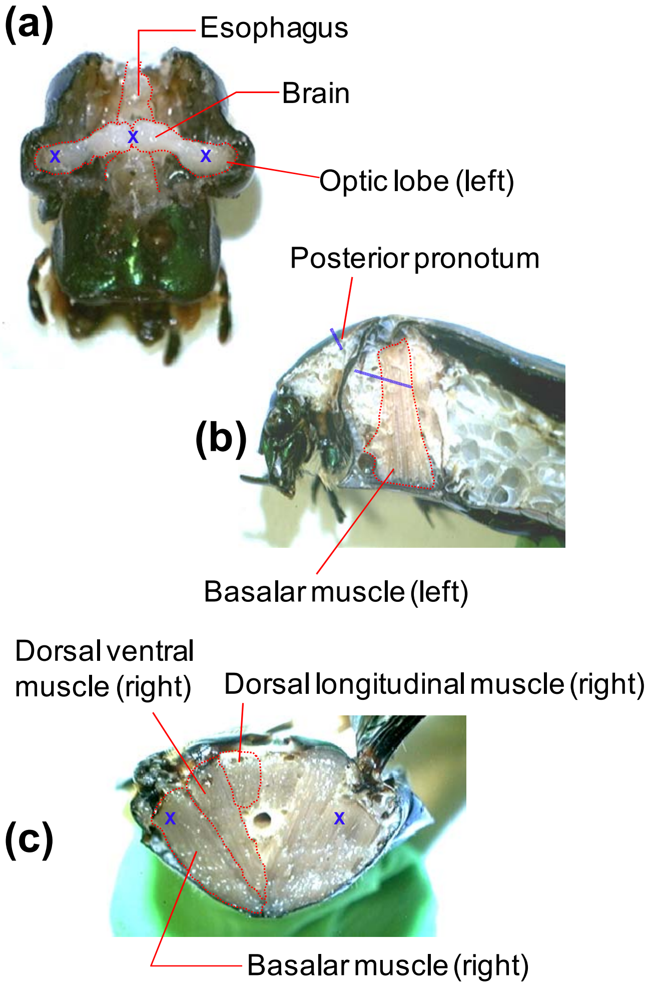

Figure 3: (a) front view of dissected beetle head showing the brain and optic lobe implant sites and relevant internal regions. (b) sagittal section of thorax showing the posterior pronotum implant (counter electrode), the basalar muscle implant (muscular stimulator) and relevant internal regions. (c) cross-section of mesothorax also showing the basalar muscle stimulator site and relevant internal regions. The basalar muscle stimulator was inserted rostral-caudal on either side of the insect, about midway between sternum and notum of mesothorax to a depth of approximately 1 cm. The letters X and bars indicate implant sites and approximate implant length, respectively. Green clay was used to support the objects in (c). Cotinis texana (which has nearly identical, scaled anatomy to the Mecynorhina beetle) was used for these anatomical images.

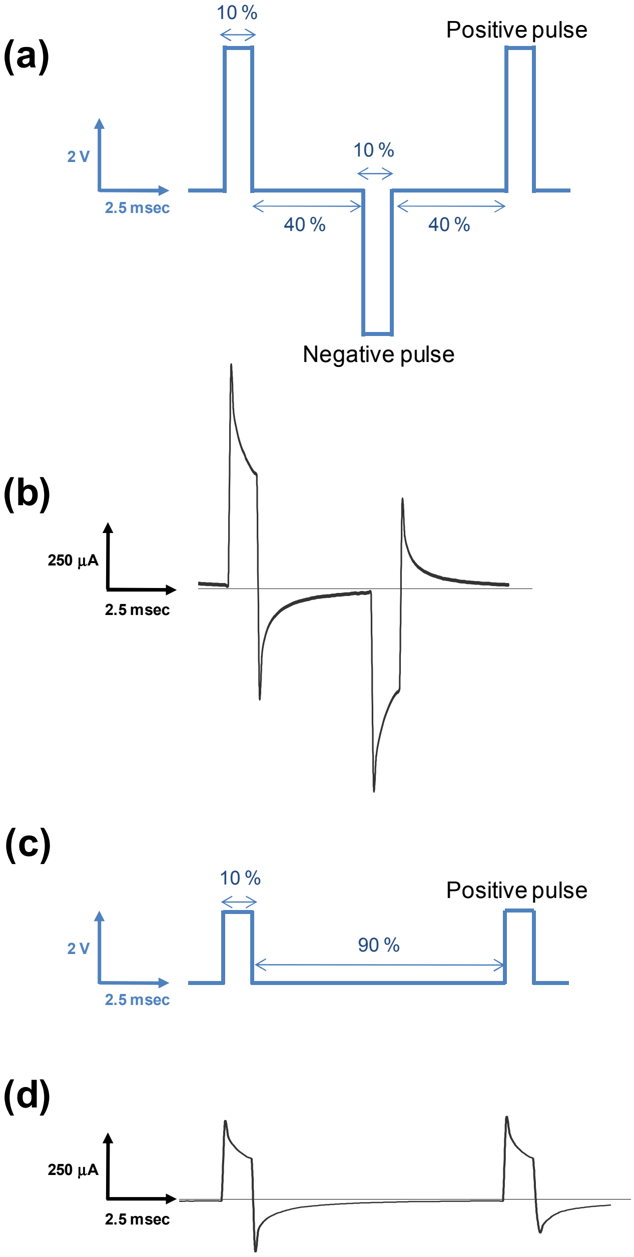

Figure 4: (a) alternating positive and negative potential pulse trains (100 Hz) applied between the left and right optic lobes for initiation of flight. (b) typical current wave monitored when applying (a), (c) positive potential pulse trains (100 Hz) applied between either left or right basalar flight muscle and the posterior pronotum (counter electrode) for eliciting turns, (d) typical current wave monitored when applying (c).

Flight Control

Flight initiation was triggered by applying a 4 V, 100 Hz, 20 % duty cycle, alternating positive and negative potential pulses (Figs. 4(a), 4(b)) to the two neural stimulators implanted into the optic lobes (Figs. 1 and 3(a)) via the mounted receiver as shown in Fig. 5 and Movie 1 in [13]. The response time was < 1 sec (N = 9); a typical, untethered beetle responded to the flight initiation command in 270 ms, as determined by frame by frame analysis in 30 fps video as shown in Figs. 5 (c) – (e). Flight cessation was triggered by a single 4 V, 1 sec pulse applied between the optic lobes.

Turn could be elicited in free flight by applying 2 V, 100 Hz positive potential pulses (Figs. 4(c), (d)) to either left or right basalar flight muscle (working electrode) with respect to posterior pronotum (counter electrode). The beetle turned in a direction opposite to stimulated side: left turn was, for example, elicited by stimulating the right basalar flight muscle. Representative turn control is shown in Fig. 6 and Move 2 in [13].

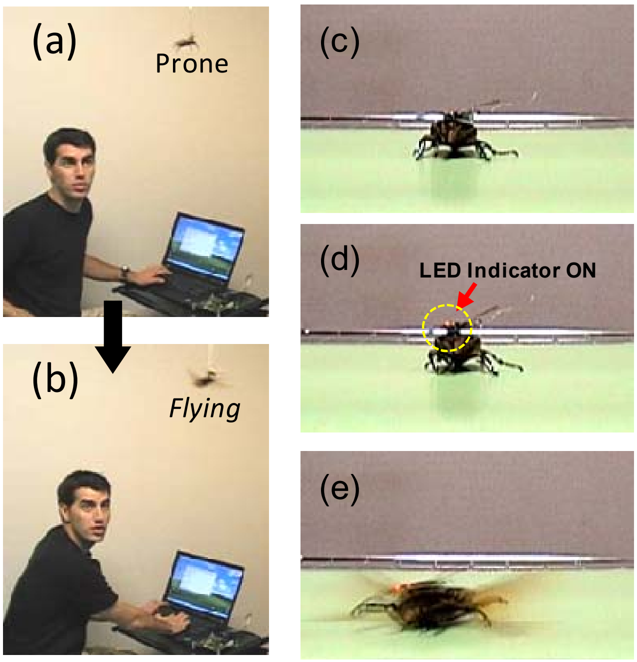

Figure 5: Photographs of flight initiation induced by the optic lobe simulator (100 Hz, 4 V amplitude, alternating positive and negative potential pulse trains between left and right optic lobes). The stimulator was wirelessly operated by user via the CC2431's built-in 2.4 GHz IEEE 802.15.4 compliant transmitter broadcasting on a single channel (1A, 2.480 GHz) using direct sequence spread spectrum RF modulation. (a) user signaled for initiation of flight, (b)beetle initiated flight. (c)-(e) close-up views of un-tethered initiation of flight. (c) standing position, (d) the LED indicator showed the stimulator turned on, (e) wings unfolded and flight started 0.27 sec after control signal was sent (b). See Movie 1 in [13].

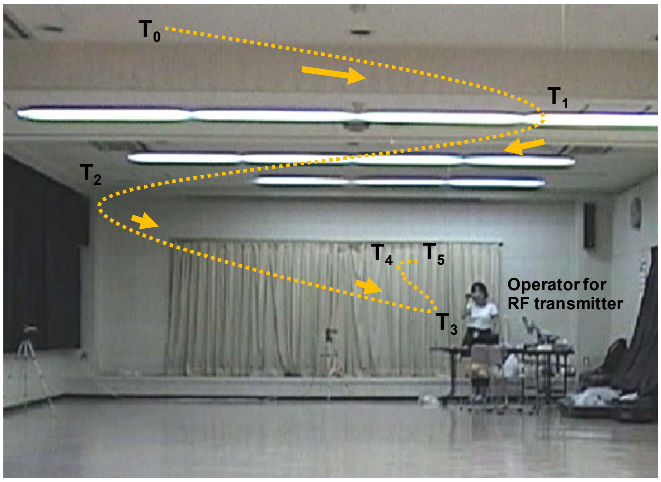

Figure 6: Flight path of a flying beetle wirelessly stimulated for turn control. The beetle was initially flying towards the operator. T_0 (0.00 sec) is the start time of the filming. At T_1 (0.6 sec), the operator signaled a left turn from the base station (right basalar muscle stimulation). At T_2 (1.6 sec), the operator switched the stimulated side from the right to the left basalar flight muscle, and the beetle turned right. At T_3 (3.1 sec), the right basalar flight muscle was stimulated (left turn). At T_4 (4.2 sec), the left basalar flight muscle and turning right again. At T_5 (4.8 sec), the beetle touched on the curtain and stopped the flight. See Movie 2 in [13] for detail.

3. CONCLUSION

We present the first-ever wireless flight control microsystem using a small RF receiver mounted on a live beetle and an RF transmitter operated from a base station. Flight initiation and cessation were accomplished by neural stimulation of both optic lobes while turns in free flight were elicited by muscular stimulation of basalar flight muscle on either side.

4. ACKNOWLEDGMENT

We thank Professor Jon Harrison (Arizona State University) for his helpful advice on insect biology and entomology. This work was financially supported by Defense Advanced Research Projects Agency (DARPA) Hybrid Insect MEMS program.

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[13] Movie files are downloadable from: ftp://ftp.eecs.umich.edu/people/maharbiz/CotinisFlightMovies/MEMS2009.