

CYBORG BEETLE: THRUST CONTROL OF FREE FLYING BEETLE VIA A MINIATURE WIRELESS NEUROMUSCULAR STIMULATOR

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ABSTRACT

We demonstrate free-flight thrust control of the cyborg beetle which consisted of a living beetle platform (*Mecynorrhina torquata*), a microcomputer backpack (neuromuscular electrical stimulator) and a micro battery. A pair of thin wire electrodes coming from outputs of the backpack was implanted into the left or right subalar muscle, a major flight muscle of the beetle. The implanted muscle was stimulated in free-flight on demand when the commands sent to the backpack wirelessly by custom software running on the operator laptop. By varying the stimulation frequency, we were able to grade the induced thrust for decelerating the beetle in the air. The achievement of free-flight thrust control would open a new realm of flight control to further complex maneuver.

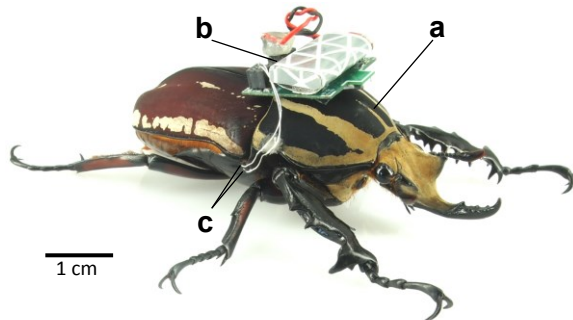


Figure 1: Photograph of a cyborg beetle; (a) live beetle platform (*Mecynorrhina*, ~6 cm, ~10 g), (b) wireless backpack assembly, (c) stimulation electrodes implanted into subalar muscle.

INTRODUCTION

The early stage of insect-machine hybrid systems, often referred to as Cyborg Insects, consisted of a living insect with a miniature analog circuit of surface mount electronics assembly mounted on, and researchers could remotely record muscle potentials of the living insect [1-4]. The advancement in micro-processor technology has allowed us to not only record but also stimulate multiple neuromuscular sites of living insect via a microcomputer tiny enough to mount on the insect. With such a stimulator, nowadays researchers can attempt to induce their desired motor actions and behaviors from the insects toward walking and flight control. Recent progress in the walking control by stimulating the nervous system of spider [5] and cockroach [6] showed the feasibility of employing living insects as the platform for a terrain legged robot. Furthermore, finding of graded response in the induced leg motion by altering the frequency of electrical stimulation of leg muscles allowed to develop a closed loop control system to regulate the insect leg to move along pre-determined motion paths [7]. For the flight control, many research groups have succeeded in flight initiation

and cessation, left-right turns of living insects. The flight initiation and cessation were demonstrated by stimulating the optic lobes of the beetle [8-10] while the turning control was achieved by stimulating the flight muscles in beetle and moth [8-11] or stimulating the nervous system to induce abdomen movements in moth [12]. A challenge ahead for more sophisticated flight control is thrust, and we have attempted to grade the speed of freely flying insect by altering stimulation parameters.

In this study, we have implemented the wireless stimulator (Fig. 2), set up a motion capture room for real-time flight path tracking (Fig. 4), and successfully achieved the graded thrust control in freely flying beetle by altering the frequency of the electrical stimulation to the subalar muscle (Fig. 3b), a major flight muscle directly inserted to the wing base.

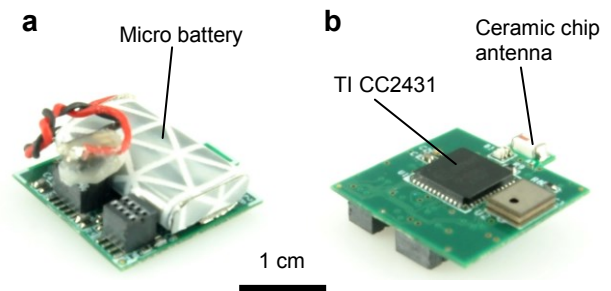


Figure 2: Wireless backpack assembly (a) top view shows two micro header for power connection and stimulus outputs with a micro battery (Fullriver, 3.7 V, 10 mAh) connected, (b) bottom view shows the Chipcon TI CC2431 microcontroller and the ceramic chip antenna (AN3216, 2.4 GHz) mounted on the PCB. Total weight is 1250 mg; microcontroller = 130 mg, battery = 345 mg, PCB + other components = 673 mg, retro reflective tape + adhesive = 102 mg.

EXPERIMENTAL PROCEDURE

Wireless Neuromuscular Stimulator Backpack

For the microcomputer backpack (neuromuscular electrical stimulator, Fig. 2), a Chipcon TI CC2431 wireless microcontroller (130 mg, 6 x 6 mm, 2.4 GHz), an AN3216 ceramic chip antenna (2.4 GHz) and other components were assembled on a custom designed printed circuit board (PCB). The backpack was mounted on the pronotum of the beetle platform with a double sided adhesive tape (Fig. 1). A micro Li-polymer battery (3.7 V, 10 mAh, 345 mg) was attached onto the backpack for the power supply (Figs. 1b and 2a).

Electrode Implantation

Mecynorrhina torquata beetle (~ 10 g, ~ 8 cm, Fig. 1a) was employed as the living insect platform. The Teflon-coated silver wire electrodes (A-M system, 127 μ m

bare diameter, 178 μm coated diameter) were burned to expose the bare silver at both terminals. Two electrodes were implanted into each subalar muscle of the beetle (Fig. 3b) with a depth of ~ 3 mm and secured with beeswax. The other terminals of the electrodes were inserted into the outputs of the backpack mounted on the beetle.

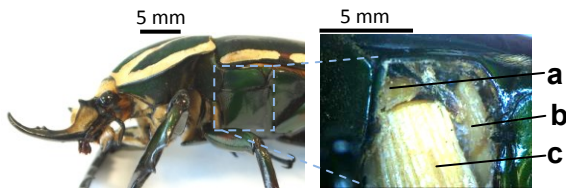


Figure 3: Anatomy of *Mecynorrhina* direct flight muscles; (left) external view of the beetle, (right) internal anatomy of the thorax exposing the direct flight muscles, (a) wing-folding muscle, (b) subalar muscle, (c) basalar muscle. These direct flight muscles inserted directly to the wing hinges and work as the micro actuators to modulate the wing kinematics.

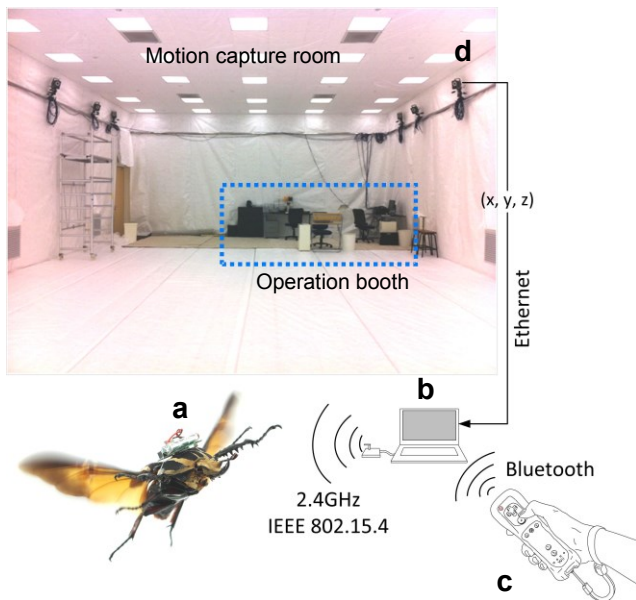


Figure 4: Free flight experiment setup for cyborg beetle in the flight capture room (9 m x 16 m x 4 m). (a) Freely flying cyborg beetle was controlled by a custom software, BeetleCommander v1.8, running on the operator laptop placed at operation booth. (b) The laptop sends control signal to the cyborg beetle wirelessly using the CC2431's built-in 2.4 GHz IEEE 802.15.4 transceiver via a USB / serial-interfaced base station. (c) A Nintendo Wii remote controller was used as user input to issue the command to the laptop via a Bluetooth transceiver. (d) 3D motion capture system of 18 T160 and T40s VICON cameras connected to the laptop via Ethernet port is used for capturing the beetle's positions. When the operator presses the Wii remote controller, it sends the command to the laptop. This command is processed by BeetleCommander v1.8 and then sent to the cyborg beetle's backpack. After receiving the command, the backpack generated pulse train to electrically stimulate the flight muscles.

Free Flight Experiment

The cyborg beetle was commanded by custom

software BeetleCommanderv1.8e running on the operator laptop that was able to manipulate the electrical stimulus parameters as multiple pulses trains (monophasic pulses, 3 V and 3 ms pulse width). The stimulating commands were sent to the backpack via the wireless communication of the backpack and the base station that connected to the operator laptop via a serial connection. For user interaction, a Nintendo Wii remote controller was implemented to send the user commands to the BeetleCommander wirelessly via a Bluetooth transceiver connected to the laptop. When the experimentalist presses a flight command button of the remote controller, BeetleCommander sends the command with predefined stimulus parameters to the backpack, which then generates an electrical stimulus to the left or right subalar muscle. For energy saving, the backpack is able to switch active/sleep mode by facing up/down the remote controller, which is automatically detected by the inertial measurement unit (IMU) of the remote controller.

After the implantation, the cyborg beetle was gently released to fly in a closed motion capture room (9 x 16 x 4, Fig. 4d) that equipped of T160 and T40s VICON cameras system. The system detected the retro-reflective taped wrapped around the battery (Fig. 2a) as a marker and reconstructed its positions in real-time. The positions of the marker were fed to the BeetleCommander for synchronizing with the stimulation commands.

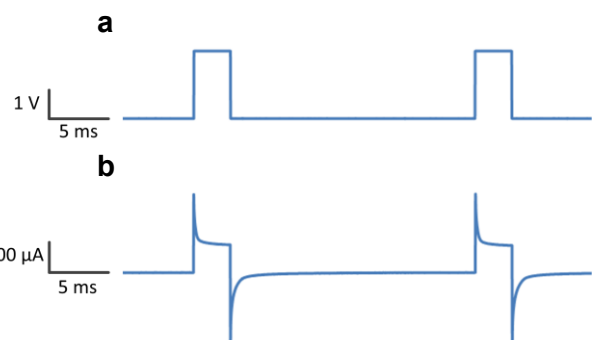


Figure 5: Stimulation waveform and electrical current flow through the subalar muscle. (a) The stimulation pulse train (3V, 3 ms pulse width and 50 Hz) from the waveform function generator was applied on the subalar muscle via the two implanted electrodes. (b) The current waveform passed through the subalar muscle.

FREE FLIGHT THRUST CONTROL

The left or right subalar muscle of a flying beetle was stimulated by 1 second multiple pulses train (3 V, 3 ms pulse width and 40 – 100 Hz, Fig. 5) for each trial (N = 14 beetles, n = 706 trials). Instead of performing left-right turnings as stimulating the basalar muscle [9, 10], the subalar stimulated beetle showed a clear decrease of flight speed during the stimulation period compared to that before the stimulation (Fig. 6). The estimated horizontal acceleration exhibited a clear deceleration. While 50 Hz – 70 Hz showed a slight decelerating effect of $\sim 0.5 \text{ m/s}^2$, the most effective range 80 Hz – 100 Hz show clearer effect with a graded response as higher frequency induced more deceleration to the flying beetle (Fig. 7).

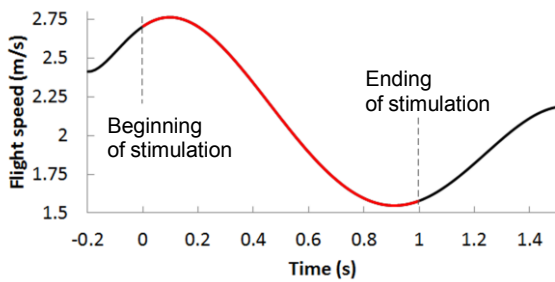


Figure 6: Representative speed profile of freely flying cyborg beetle during the stimulation of subalar muscle. The red line indicates the speed of the beetle during the stimulation while the black one shows the speed of the beetle without stimulation. The speed of the beetle reduced during the stimulation and started to recover when the stimulation ended. The beetle was stimulated by 1s stimulus train of multiple pulses (3V, 3 ms, 100 Hz).

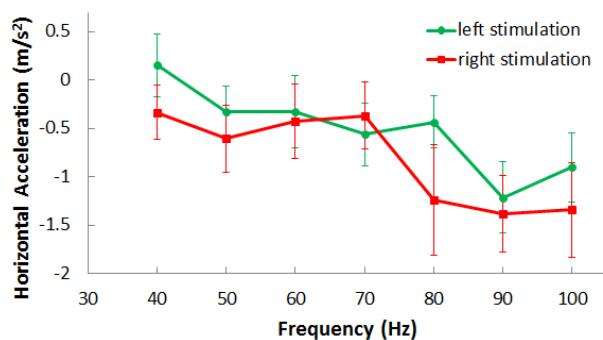


Figure 7: Horizontal acceleration of cyborg beetle induced by the stimulation of subalar muscle in free flight. The stimulation decelerated the flight speed of the beetle with the most effective range from 80 Hz to 100 Hz. The deceleration of flight speed is associated with the reduction of beetle's thrust. Error bars denoted 90% confidence interval ($N=14$ beetles, $n = 706$ trials).

The stimulation of subalar muscle also exposed an ultralow power consumption that is $\sim 200 \mu\text{W}$ ($N = 3$ beetles, $n = 150$ trials). It would help the system save energy efficiently and enhance the working duration of the cyborg insect when using the micro battery.

CONCLUSION

We demonstrated the achievement of thrust control by wirelessly stimulating the subalar muscle for decelerating the untethered flying beetle. This capability would open a new realm of flight control to further complex maneuver as hovering and landing.

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REFERENCES

- [1] W. Kutsch, G. Schwarz, H. Fischer, and H. Kautz, "Wireless Transmission of Muscle Potentials During Free Flight of a Locus," *J. Exp. Biol.*, vol. 185, pp. 367-373, 1993.
- [2] N. Ando, I. Shimoyama, and R. Kanzaki, "A Dual-Channel FM Transmitter for Acquisition of Flight Muscle Activities from the Freely Flying Hawkmoth, *Agrius convolvuli*," *J. Neurosci. Methods*, vol. 115, pp. 181-187, 2002.
- [3] H. Fischer, H. Kautz, and W. Kutsch, "A Radiotelemetric 2-Channel Unit for Transmission of Muscle Potentials During Free Flight of the Desert Locust, *Schistocerca gregaria*," *J. Neurosci. Methods*, vol. 64, pp. 39-45, 1996.
- [4] P. Mohseni, K. Nagarajan, B. Ziaie, K. Najafi, and S. B. Cray, "An Ultralight Biotelemetry Backpack for Recording EMG Signals in Moths," *IEEE Trans. Biomed. Eng.*, vol. 48, pp. 734-737, 2001.
- [5] Z. Yang, K. Y. Chun, J. Xu, F. Lin, D. Li, and H. Ren, "A Preliminary Study of Motion Control Pattern for Biorobotic Spiders," in *Proceedings IEEE 11th International Conference on Control & Automation (ICCA) 2014*.
- [6] T. Latif, E. Whitmire, T. Novak, and A. Bozkurt, "Towards Fenceless Boundaries for Solar Powered Insect Biobots," in *Proceedings 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2014.
- [7] F. Cao, Z. Chao, T. T. Vo Doan, Y. Li, D. H. Sangi, J. S. Koh, et al., "A Biological Micro Actuator: Graded and Closed-Loop Control of Insect Leg Motion by Electrical Stimulation of Muscles," *PLoS ONE*, vol. 9, 2014.
- [8] M. M. Maharbiz and H. Sato, "Cyborg Beetles," *Sci. Am.*, vol. 303, pp. 94-99, 2010.
- [9] H. Sato, Y. Peeri, E. Baghoomian, C. W. Berry, and M. M. Maharbiz, "Radio-Controlled Cyborg Beetles: A Radio-Frequency System for Insect Neural Flight Control," in *Proceedings IEEE 22nd International Conference on Micro Electro Mechanical Systems (MEMS)*, 2009, pp. 216-219.
- [10] H. Sato, C. W. Berry, Y. Peeri, E. Baghoomian, B. E. Casey, G. Lavella, et al., "Remote Radio Control of Insect Flight," *Front. Neurosci.*, vol. 3, 2009.
- [11] A. Bozkurt, R. F. Gilmour, and A. Lal, "Balloon-Assisted Flight of Radio-Controlled Insect Biobots," *IEEE Trans. Biomed. Eng.*, vol. 56, pp. 2304-2307, 2009.
- [12] A. J. Hinterwirth, B. Medina, J. Lockey, D. Otten, J. Voldman, J. H. Lang, et al., "Wireless Stimulation of Antennal Muscles in Freely Flying Hawkmoths Leads to Flight Path Changes," *PLoS ONE*, vol. 7, 2012.

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