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AERIAL and TERRESTRIAL LOCOMOTION CONTROL of LIFT ASSISTED INSECT BIOBOTS

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Abstract— **This paper presents results on remote control navigation of moths implanted with neuromuscular probes. We have previously demonstrated that the technique of metamorphosis based surgical insertions enables the concept of "insect-based" centimeter scale biobots. Here, we demonstrate for the first time, the control of gait with a radio controlled, balloon-suspended, electrode-instrumented *Manduca sexta* by altering the direction of turn through applied neuromuscular pulses. We also present sustained flight control in *Manduca sexta* with demonstration of take-off, controlled yaw, and controlled landing. The assist of the helium balloon for lifting payloads allows for a wide-range of application space where insect biobots can be deployed.**

I. INTRODUCTION

INSECT flight has fascinated and inspired engineers for many decades because of its near impossibility on aerodynamic principles. Several technical approaches have been explored to develop insect-mimetic small scale autonomous flying vehicles based on man-made propulsion and power components [1]. However, demonstration of an insect-like aerodynamic performance has not been possible yet. Alternatively, one can directly tame insect function in a "biobotic" manner by electrical control of its nervous system. We have previously demonstrated metamorphosis based surgical techniques to implant electronic systems into the insect body [2], where we were able to direct the flight of the tethered hawkmoth *Manduca sexta* [3,4] through pupal stage inserted neuromuscular probes. The inserted structures are adopted by the body and insertion related injuries are auto-repaired as a result of metamorphic tissue reformation. Therefore, a mechanically secure electrical coupling was obtained with the insect tissue for biobotic actuation of the neuromuscular system. Following our initial demonstrations, other groups also have presented similar achievements either by using different insects [5], by actuating other anatomical parts of the *Manduca sexta* [6] or by using different forms of actuation mechanisms [7].

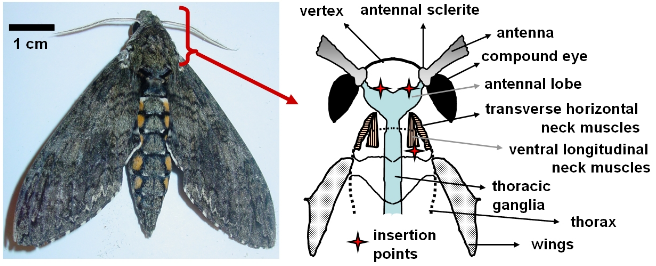

Figure 1: The anatomical description of *Manduca sexta* head-neck anatomy

In this paper, we demonstrate aerial and terrestrial locomotion control of electrode-instrumented tobacco hawkmoth Manduca sexta. During its flight, these insects detect chemical cues released from sources of food, host plant or opposite sex through their antennal lobes. They then rotate their head through their neck muscles towards the target location and use the visual information obtained through their compound eyes to direct their locomotion [8]. In this study, we have worked towards remotely stimulating the antennal lobe and the neck muscle of the hawkmoth Manduca sexta (Figure 1), with the aim of obtaining flight direction towards the stimulated side. We also investigated the terrestrial control of wing-removed Manduca sexta by using the same actuation mechanism to widen the application space of the metamorphic insertion based insect biobots.

The payload capacity of most insects is limited to subgram weights, which restricts the application space of aerial and terrestrial insect biobots. To overcome this obstacle, we benefited from the lifting force of helium balloons to assist the insect to carry the weight of the additional payload. Assistance with lifting potentially increases mission duration by conserving biological energy and also allows for attachment of extra electronic components for various applications.

II. EXPERIMENTAL METHODS AND PROCEDURES

A. Radio Controlled Muscle Stimulator

The modular radio controlled insect stimulator platform consists of four parts: probe, power, control electronics and balloon (Figure 2). To build the probes, biocompatible platinum-wire electrodes were soldered on a tiny PCB and shaped for the antennal lobe and the neck muscle insertion (Figure 2). The copper traces on this PCB matches a connector on the radio control board. Therefore, the same radio can be re-used several times for different insects. The

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probes, however, are disposed with the insect when they complete their adult lifetime.

A two-joystick, 72MHz AM transmitter (Futaba, Inc.) was used to remotely send a PPM (Pulse-Position-Modulation) stream to the receiver located on the insect (Figure 3). A super-regenerative receiver was custom built to receive the signal. A microcontroller (PIC12F615) was used to separate the PPM stream into different channels and convert it to pulse-width-modulated (PWM) waveforms, which were applied to the tissue (Figure 3). The position of the joystick on the transmitter determines the duty cycle of the PWM pulses, therefore the amount of charge injected into the tissue. The radio and electronics, weighing 650 mg, consumes 750µWatts static, and 1 mW dynamic power.

To power the radio and the microcontroller, a rechargeable Li-Po battery (3.6volts, 8.5mAh, 300mg) was connected to the PCB holding the electronics through FFC/FPC connectors. This allows for easily attaching and detaching of the batteries to turn the system on and off. The batteries last more than 5 hours with continuous pulsing.

A helium filled latex balloon was used to assist the insect with the payload weight lifting. Tiny magnets were used to attach/detach the helium balloon to the insect (Figure 4). The lifting force of the balloon (1gr/l) was balanced with the weight of the insect and the electronic payload (~3gr).

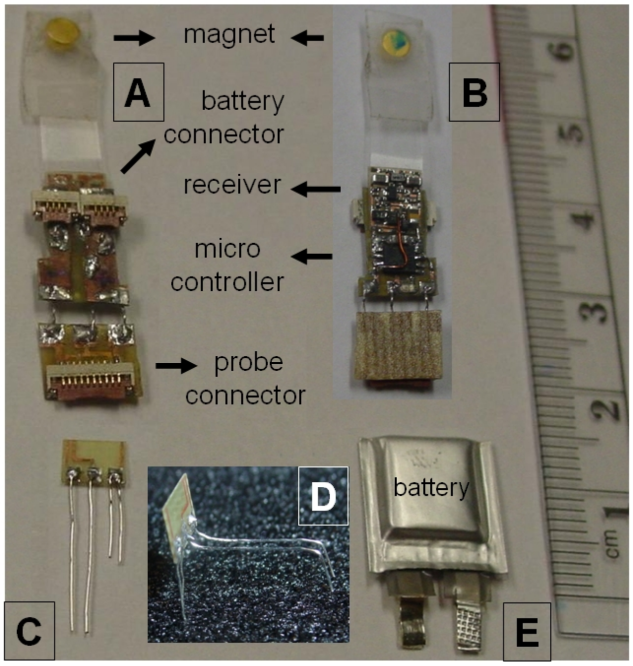

Figure 2:. The radio controlled neuromuscular stimulating system. Front side of the assembled radio board (A) consisting of the microcontroller and the receiver (weight 70mg). The backside of the board (B) with FFC/FPC connectors for the micro probe assembly (C) and the battery (E). 3D bending of the wire-electrodes (D) to target thorax and antennal lobe (diameter 200µm). Magnets taped to the circuit (A-B) are used to connect with the balloon.

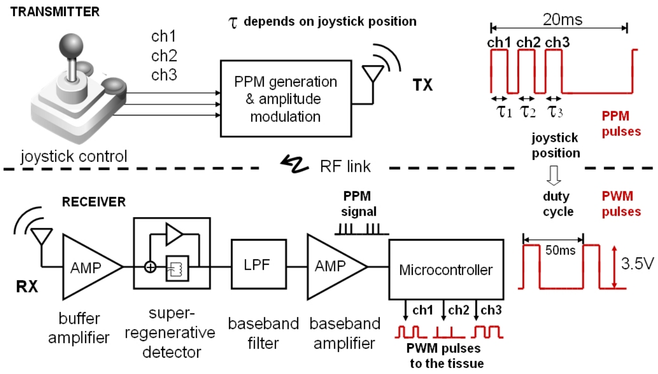

Figure 3: Pulse shaping at transmitter and processing at receiver sides of the radio system. The position of the transmitter joysticks determines the frequency and duty cycle of the pulses going to the antennal lobe and neck muscles of the insect.

B. *Surgical Insertions*

Insects were obtained from the Boyce Thompson Institute insect growth facility. The wire-electrode based probes were inserted into the pupae under anesthesia 7 days before emergence (Figure 5) and insects were kept in an incubator with a light-dark cycle of 17/7 hours. For the terrestrial experiments, adult insects were anesthetized and the wings were removed using sharp surgical scissors. No behavioral disturbance of the insect was observed due to wing removal, as expected, since the wings are passive cuticular airfoils.

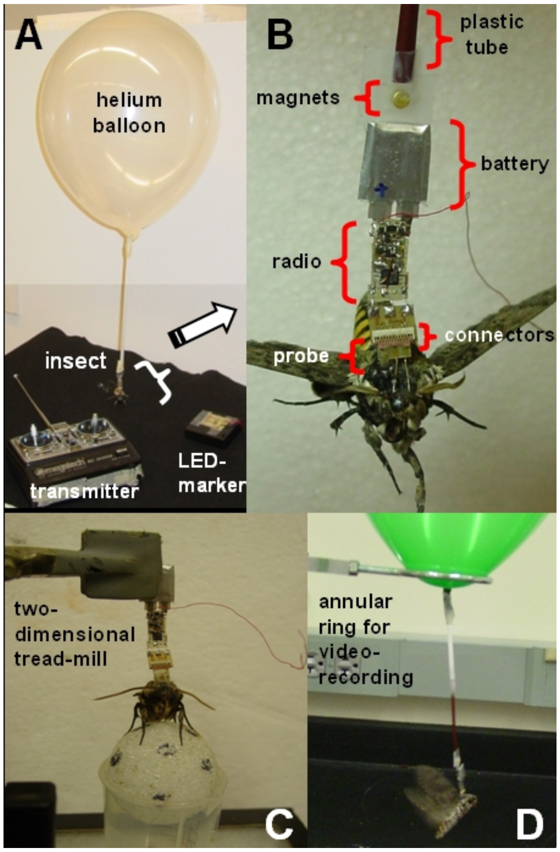

Figure 4: Description of the balloon assisted flight setup with the retaining ring inserted for stable recording purposes.

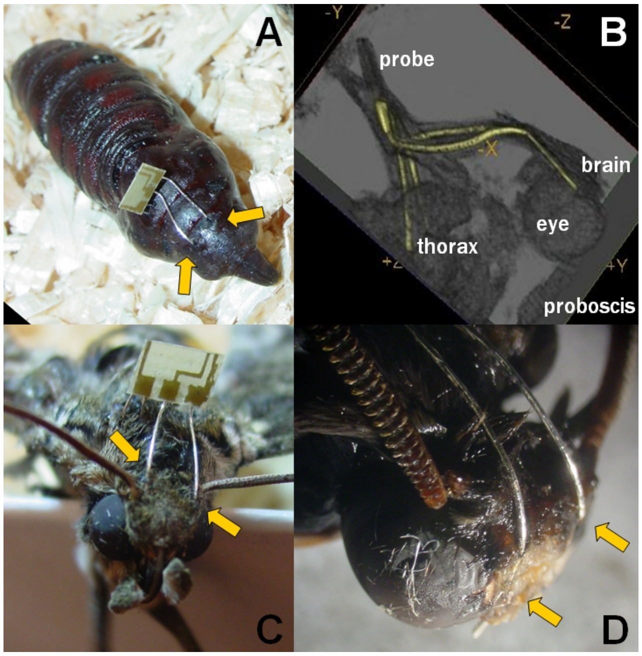

Figure 5: Arrows indicating insertion points of the probe on the pupal stage (A) and on emerged adult insect (C). Probe adoption by the brain tissue (D) revealed with the removal of the vertex (front part of the head). Location of the metal-wires (lighter-color) in the thorax and brain on the reconstructed X-ray images (B).

C. *Flight and Gait Experiments*

Two sets of experiments were performed both for aerial and terrestrial locomotion direction. In the first set, the locomotion of the insects was restrained for a close-up camera investigation by introducing a restricting annular ring around the stick-connector connecting radio to the balloon in aerial case (Figure 4). For terrestrial control, the insect was placed on a low friction foam-ball, which acted like a two-dimensional treadmill (Figure 4). Later, these restrainers were removed and the behavioral changes with applied pulses were observed and video recorded during balloon assisted free-flight and -walk. Later, these videos were digitized to be analyzed in a computer environment.

III. RESULTS AND DISCUSSIONS

The probes emerged with the insect 7-days after insertion (Figure 5). The successful rate-of-emergence was 84% (N=30) and 80% of these adults successfully inflated their wings. Natural healing and tissue-growth around the inserted probes (Figure 5) provided a secure attachment of the payloads to the insect, which required forces of 2-Newtons for extraction. The radio electronics was connected to insect-mounted electrodes, taking only a few seconds (Figure 4).

The remote actuation of the targeted regions caused wing flapping in a resting moth, indicating successful electrical coupling (3MΩ/cm impedance at DC). In the restrained set-up, flight was initiated with pulses sent to the antennal lobe (3.5Vpp-20Hz-50% duty cycle). During flight, the neck muscles were actuated with similar pulses, which elicited controlled yawing of the insect (~60-80º/s). Flight could be terminated immediately with antennal lobe stimulation with high frequency pulses (3.5Vpp-50Hz-50% duty cycle). Unrestrained free flight was successfully enabled by removal of the annular ring. We were able to demonstrate a three-task mission of lifting-off, yawing and landing with freely flying insects (typical trajectory in Figure 6). To exhibit reproducibility, we repeated the same mission three consecutive times on three different trials with consistent results. All of these results can be best seen in movie-format [9].

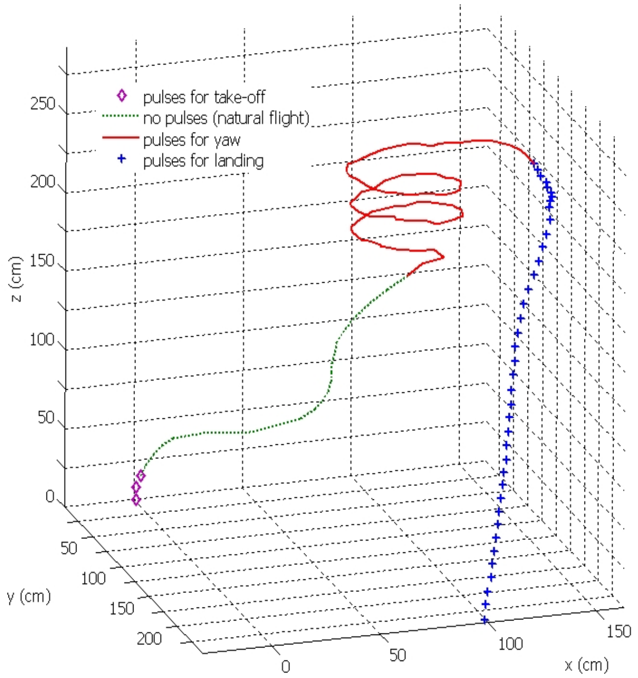

Figure 6: Digitized flight track of the moth as a result of applied stimulation pulses. The flight control can be best seen in video format [9]. Circular flight control is demonstrated by the red circular trajectories.

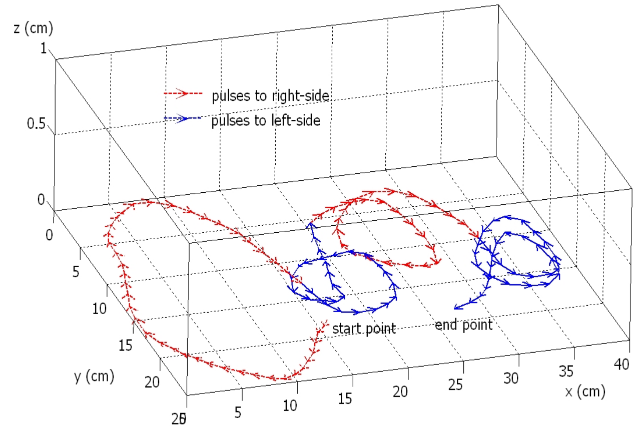

Figure 7: Digitized walking track of the moth as a result of applied stimulation pulses. The gait control can be best seen in video format [9].

Similar pulses were applied to the wing-removed insect for terrestrial control. On the two-dimensional treadmill, actuation of each side caused rotation of the ball towards the opposite direction (~360º/s) simulating the turning of the insect towards the actuated side. When the insect was released for a free-walk, the continuous actuation of one side caused the insect to follow a circular path in that direction. We were able to demonstrate a mission of following "8" shaped routes with these freely moving insects (typical trajectory in Figure 7) [9].

IV. CONCLUSION

The metamorphosis based surgical insertions of artificial structures to the insects enables a hybrid biological and technological pathway towards obtaining remote controlled insect biobots/cyborgs. Here, we present successful demonstrations of locomotion control on both land and air through electrodes inserted using this pathway. By feedback controlled learning of yaw and rotation motion obtained in various insects, it is plausible to ascertain the best positions for probe placement and optimized pulse sequences for improved precision, a study currently underway.

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