Abstract—We report on radio-controlled insect biobots by directing the flight of Manduca sexta through neuromuscular activation. Early metamorphosis insertion technology was used to implant metal wire probes into the insect brain and thorax tissue. Inserted probes were adopted by the developing tissue as a result of the metamorphic growth. A mechanically and electrically reliable interface with the insect tissue was realized with respect to the insect’s behavioral and anatomical adoption. Helium balloons were used to increase the payload capacity and flight duration of the insect biobots enabling a large number of applications. A super-regenerative receiver with a weight of 650 mg and 750 μW of power consumption was built to control the insect flight path through remotely transmitted electrical stimulation pulses. Initiation and cessation of flight, as well as yaw actuation, were obtained on freely flying balloon-assisted moths through joystick manipulation on a conventional model airplane remote controller.

Index Terms—Biobots, flight control, implantable electrodes, insects, micro-air-vehicles (MAV), radio control, surgery.

I. INTRODUCTION

For many decades, insect flight has fascinated robotic engineers confronting challenges in realizing man-made centimeter-scale flying machines. Insects are self-powered, operate with highly efficient flight muscle actuators, and carry onboard flight control sensors as well as collision avoidance systems to perform exquisite acrobatics. Several technical approaches have been explored to develop insect-mimetic small-scale autonomous flying machines [1]. However, it has not been possible to reach the long mission duration and aerodynamic performance and maneuverability of insects because the artificial flight actuators are not sufficiently efficient and the power and energy density of power sources are inadequate for insect-like flight [2].

Another idea has been to directly tame and domesticate the insect function in a “biobotic” manner by tapping into the nervous system with artificial electronic systems [3]. However, these methods require delicate microsurgery skills to accurately place electronics in the insect tissue, where the resultant injury has the potential to affect flight performance. It has also been challenging to develop permanent and reliable attachment methods to fix electronic payloads to the insect’s body, which is covered with weakly attached scales and piles. In order to solve these issues with adult-stage biobot interfaces, we have previously demonstrated surgical techniques [early metamorphosis insertion technology (EMIT)] to implant artificial systems into the insect body [4], [5]. In this method, electronic and mechanical components are introduced into the insect body during early metamorphic stages (Fig. 1), where the metamorphic growth around the implant provides a strong mechanical attachment, as well as reliable electrical coupling [6]. Moreover, the surgical procedure is relatively simpler and performed only in seconds, which potentially enables batch processing and mass production of such insect biobots. When the adults emerge, these pupal-stage inserted implants provide a hybrid machine–insect platform for various biorobotic studies.

The flight control system of moths consists of sensory organs connected either directly to the brain or to the ganglia distributed along the body (Fig. 2). Environmental signals received through these sensors are converted into orderly contractions of muscle groups after being processed by the ganglia. Various parts of this system can be stimulated to alter its natural operation in order to direct the control of flight using external electronics. It is well established that during natural flight, moths sense various chemical stimuli through their antennal lobe [7], and maneuver toward targeted locations such as nectar sources and host plants.

Fig. 1. Life cycle of Manduca sexta with stages of EMIT, as indicated.
[8]. They also use their eyes to detect the visual cues to find and recognize these targets. Insect eyes are part of the exoskeleton and can only be moved with the head to stabilize the retinal image of the target. During yaw, for example, the contraction of the wing muscles is preceded by the rotation of the head toward the aimed direction. Therefore, the neck muscles are directly involved in motion directivity [9]. In this study, we have worked toward stimulating the antennal lobe and the neck muscle of the hawkmoth *Manduca sexta*, with an aim of obtaining locomotion toward the stimulated side to prove the concept of the EMIT-based remote-controlled biobotic platforms.

II. MATERIALS AND METHODS

The modular remote-controlled insect stimulator platform consists of three layers: probe, power, and control electronics (Fig. 4).

A. Design and Fabrication of Stimulation Probe

The control electronics is connected to the neuromuscular system through the stimulation probe. The probe consists of biocompatible gold or silver wire electrodes (diameter 200 µm, A-M Systems, Inc.) soldered to a printed circuit board (PCB) probe body (FR-4, 4 × 5 mm²). The geometry of the electrodes was designed to target a region spanning the antennal lobe and the neck muscles [Figs. 2 and 4(c)]. During the EMIT procedure, the wire electrodes are positioned in the pupal tissue and the PCB is exposed outside [Fig. 5(a)]. After the adult insect emerges, the control electronics is connected to the probe through a flat flex cable (FFC) connector [Fig. 4(f)]. The copper traces (200 µm) on the probe body [Fig. 4(d)] match this connector. The manufactured probe weighs approximately 30 mg. We used silver and gold wires as stimulation electrodes due to low flexural rigidity, biocompatibility, and lower cost. Although their stability to electrolytic corrosion is not as good as that of some other noble metals (such as platinum or iridium) [10], the softness/flexibility of the wires is required to mechanically match the forces encountered during the insect-head rotation.

B. Radio and Control Electronics Design

For the transmitter, we use a conventional two-joystick, three-channel, 72 MHz AM transmitter (Futaba, Inc.), which is widely used for radio-controlled (RC) micro-air-vehicles, model air-planes, and helicopters. To receive and demodulate the transmitted pulse position modulation (PPM) stream (Fig. 3), a super-regenerative-based receiver architecture was custom built on an FR-4 PCB [Fig. 4(e)]. This architecture requires fewer electrical components, and therefore weighs less and consumes minimal power as a result of self-oscillatory and self-quenching advantages of the “super-regeneration” principle [11]. A microcontroller (PIC12F615) was also connected to the receiver output to separate the PPM stream into different channels and convert it into pulsewidth-modulated waveforms to be applied to the tissue. The position of the transmitter joysticks determines the frequency and duty cycle of these pulses going to the antennal
and 80% of these adults were able to successfully insert the probe by being kept at 4 °C for 30 min. After the insertion, the insects were kept at a dark/light cycled incubator (7 h dark at 18 °C, and 17 h light at 27 °C) until emergence. During the development occurring in the incubator, the probes are naturally secured to the insect body by cuticle healing and tissue growth around the probes [6].

C. Surgical Insertions

Insects were obtained from the Boyce Thompson Institute insect growth facility. The probes were surgically inserted into the insect using the EMIT procedure [6] around seven days before eclosion [Fig. 5(a)]. The insertion procedure involves driving the electrode wires through the outer cuticle of the pupae at the targeted locations. The pupae were anesthetized before the insertion by being kept at 4 °C for 30 min. After the insertion, the insects were kept at a dark/light cycled incubator (7 h dark at 18 °C, and 17 h light at 27 °C) until emergence. During the development occurring in the incubator, the probes are naturally secured to the insect body by cuticle healing and tissue growth around the probes [6].

D. Balloon-Assisted Flight

*Manduca sexta* can carry up to 1 g of payload. However, as the payload weight increases, the flight distance (from kilometers for 0 g to ~5 m for 1 g) and duration (from hours for 0 g to ~50 s for 1 g) decreases (unpublished observations). This limits the application space of the aforementioned biobotic platforms. To overcome this problem, we introduce the concept of balloon-assisted insect flight, which reduces the effective weight lifted by the insect flight [13]. For this purpose, we attached a helium balloon to the electronics board using two magnets, one glued to the balloon side and the other to the PCB holding the radio [Fig. 4(b) and (e)]. The lifting force of the balloon was balanced with the weight of the insect and the electronic payload. To record the effect of the actuation in close-up view, we first introduced an annular ring around the plastic tube between the balloon and electronics board [Fig. 4(a)]. Then, the annular ring was removed for free-flight experiments, consisting of taking-off, yawing, and landing by sending pulses from the remote controller.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The adult insects emerged from pupae 5–7 days after the surgical insertions [Fig. 5(b)] with an average weight of 2.2 g (only male adults were used). The successful emergence rate was 84% (%N = 30) and 80% of these adults were able to successfully inflate their wings. The healed cuticle at the insertion point can be seen in Fig. 5(b). This healing and the tissue growth around the inserted probe [Fig. 5(c)] provided a secure attachment of the payloads to the insect, as a result of which, the EMIT procedure eliminated the need for artificial glues. Typical forces required to pull the probes out of the insect body were 2 N, demonstrating the strength of the mechanical coupling to the tissue. After the emergence, we were able to easily connect the control electronics and power layers to the probe body through the FFC connector in 5–10 s without requiring any anesthesia [Fig. 4(b)].

The helium balloon with 3 L of volume was able to lift the insect with the added electronics. In addition to increasing the payload capacity, the lift provided by the helium (1 g/L) helped the insect to conserve the energy used for lifting its own body weight, thereby potentially increasing the mission duration. This approach also allows for addition of other electronic components, such as extra power sources for extended mission duration, sensors for environmental sensing, cameras for surveillance, and actuators for further detailed control of the insect flight.

The actuation of the targeted regions with electrical pulses sent from the transmitter to the antennal lobe caused wing flapping on a resting moth, indicating successful electrical coupling. A typical dc resistance of the order of 3 MΩ/cm was measured between the wire electrodes. In the setup with the annular ring, we were able to initiate natural flight with pulses sent to the antennal lobe (3.5 Vpp~20 Hz~50% duty cycle). After the flight was initiated, actuation of the neck muscles with similar pulses elicited controlled yawing of the insect (~60°/s~80°/s). The flight ceased immediately when the antennal lobe was stimulated with high-frequency pulses (3.5 Vpp~50 Hz~50% duty cycle). When the annular ring was removed, we were able to demonstrate a three-task mission of lifting-off, yawing, and landing by sending pulses from the remote controller.

Fig. 5. (a) Arrows indicating insertion points of the probe on the pupal stage and on (b) the emerged adult insect. (c) Probe adoption by the brain tissue revealed with the removal of the vertex (front part of the head). (d) Location of the metal wires (lighter color) in the thorax and brain on the reconstructed X-ray images.
Fig. 6. Digitized flight track of the moth as a result of applied stimulation pulses. The flight control can be best seen in video format [14].

with freely flying insects. A typical trajectory of the insect position obtained during this mission can be seen in Fig. 6. To exhibit reproducibility, we repeated the same mission three consecutive times in three different trials. All of these results can be best seen in movie format [14]. By feedback-controlled learning of the yaw motion obtained in various insects, it is plausible to ascertain the best positions for probe placement and optimized pulse sequences, a study currently underway.

IV. CONCLUSION

In this study, we demonstrated radio-controlled stimulation of an insect neuromuscular system to control its flight. The EMIT process was used to successfully integrate stimulation probes to the insect tissue. Metamorphic growth after the surgery provided melding metal wires and targeted actuation locations: the antennal lobe and the neck muscles. Simplicity of the surgical procedure allows for batch processing and mass production of these hybrid insect–machine systems. Electrical pulsing of the targeted locations created flight initiation, cessation, and yaw maneuver on the insects whose flights were supported by the lifting force of helium balloons. The concept of balloon-assisted flight allows for transport of tens of grams, enabling a vast number of engineering applications. This work paves the way for future engineering approaches to understand the insect flight in more detail and also to facilitate insect-based biobotic systems as centimeter-scale micro-air-vehicles.

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