Insect interfaces
EE519 Seminar

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***Abstract*—This review examines recent advancements in insect technology research, focusing on innovations such as electrical muscle stimulation, neurostimulation, and early metamorphosis implantation technology (EMIT). These techniques enable precise control over insect locomotion and behavior, unlocking their potential in diverse practical applications. Key areas of impact include neuroscience, environmental monitoring, search and rescue missions, and agricultural practices. While these advancements highlight the adaptability, efficiency, and robustness of insects as platforms for biohybrid systems, they also raise significant ethical concerns. The integration of living organisms with artificial technologies challenges existing norms, yet ethical considerations remain underexplored in much of the current literature. This review seeks to provide a balanced perspective on the technical achievements and practical applications of insect-based technologies, while underscoring the need for a deeper ethical discourse to guide future developments.**

I. Introduction

Highly miniaturized CMOS electronics on micromachined probes has enabled complex brain–machine interfaces (BMI) but it also catalyzed the development of biohybrid insect systems, a revolutionary field in robotics and bioengineering. These systems merge living insects with microelectronics, enabling precise control over movement and behavior. By harnessing the inherent adaptability, resilience, and energy efficiency of insects, researchers have achieved remarkable advancements across various domains, including neuroscience, environmental monitoring, search and rescue, and agriculture.

Innovative techniques such as electrical muscle stimulation, neurostimulation, and early metamorphosis implantation technology (EMIT) have been pivotal in these developments. These approaches allow for the modulation of insect locomotion and behavior, offering new possibilities for maneuverability and adaptability in complex environments. For instance, controlled insect swarms could revolutionize disaster response scenarios, while targeted behavioral modifications may enhance precision in agricultural pest control.

This emerging field not only provides insights into the fundamental principles of biological sensorimotor control but also inspires the design of energy-efficient, bioinspired robotic platforms. As these technologies continue to evolve, biohybrid systems hold the potential to address challenges in robotics and beyond, while also raising critical questions about the ethical implications of integrating living organisms with artificial systems.

II. Insect Motion and Control Mechanics

Numerous studies feature stimulation of the motion mechanism. Here we will focus on different experiences to overview the various stimulation possibilities.

A. Backpack electrode stimulation

Flight stimulation can be obtained by placing somewhat of a backpack on the insect we want to study (Beetles and Moths in [1] studies). To enable stimulation during long and complex controlled flights, we need memory, programmability, efficient radio systems and onboard digital processing. Therefore, the backpack generally contains a multiple-channel system built around a microcontroller (Figure 1). To study flying habits, it is required to introduce extern input and bias the free-flight trajectory of the insect. The system implemented to do so, is to identify the biological control loop and interfere with it by wrapping another loop, a synthetic one, around it. Those backpacks, or other similar items, allow two different type of stimulation: *Muscle stimulation* and *Neurostimulation*. [1]

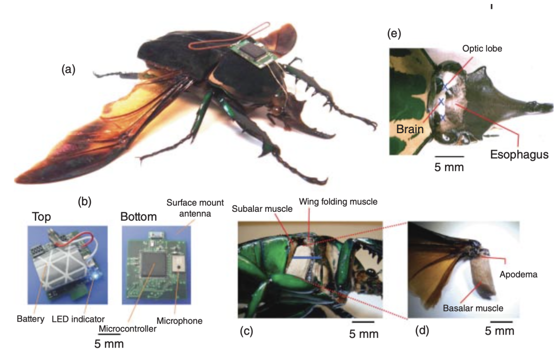


Fig. 1: A beetle hybrid system. (a) Overview of the stimulator-mounted beetle. (b) The beetle stimulator has a surface mount ceramic antenna. (c–e) anatomical pictures of stimulation site. Figure from [1]

B. Muscle stimulation

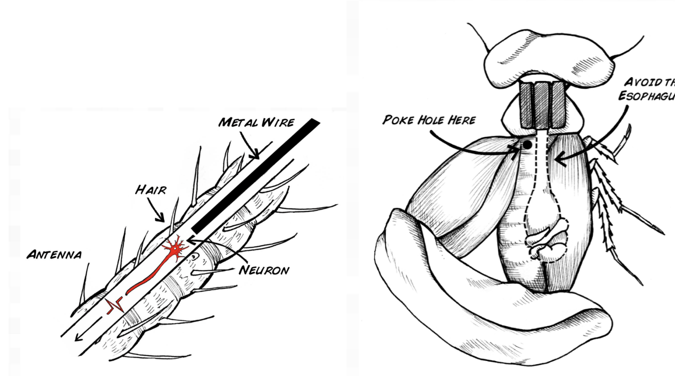
1) Neck muscle stimulation: Whether it is light, food or a possible companion, insects flight trajectories often depend on visual cues. One specific thing about our subjects is that for most insects, their eyes cannot move to track targets, therefore the following of a visual stimulus often induces strong motion of the head. The exploitation of this feature allows us to induce right or left turns in flying moths, by electrically stimulating their neck muscles. This method finds itself very useful, because it avoids the risk of damaging wing muscles, which work in a much more complicated linkage. [1]

2) Computer control of swarm of roaches: Although most insect related studies concern flying habits, we could benefit a lot from the control of their legs as well. Hirotaka Sato Group (Nanyang Technological University in Singapore) has enabled the control of movement mode and speed of beetles and roaches by stimulating their leg muscles. Although for now it is only applied to one insect at a time, Dr. Hirotaka Sato hopes to reach computer control of an entire swarm. This idea, which could look spine-chilling to many, has a promising future in the saving of earthquake victims. Cockroaches, being very robust crawling insects, would have no problem exploring the rubble. Equipped with temperature sensors, it would be possible to control them to go towards the people stuck, and indicate their location for them to be saved much more quickly. [2] [3]

C. Neurostimulation

1) Flight initiation: Neurostimulation studies have been done to learn about initiation of flight. It was known that *Mecynorhina ugandensis* beetles will not fly in the dark. Abrupt darkening while flying will almost immediately make them stop and they do not initiate takeoff in the dark either. Two electrodes were then implemented near the bases of the left and right optic lobes, and potential pulses between them were applied. It was found that bi-phasic square pulses of 1 ms pulse and 4 ms pitch enabled flight 0,5 seconds after the first stimulation. Note that the variation in stimulation voltage between 2 to 4 V did not change the number of pulses required to take off. Those artificially induced flights were adopted with a normal posture of the insect, whom kept on flying even after the stimulus was turned off. In contrast, cessation of flight was caused by a longer pulse, leading to the clamping of voltage between the lobes. [1]

2) The "RoboRoach" experimentation kit: A very specific tool that insects possess are their antennas. Those are actively sensing the surrounding environment, and avoid the insect to walk straight into a wall. When the antenna hits an obstacle, an action potential is fired in the connected neuron, encouraging the insect to turn the other way. Those can be exploited in fooling the animal by giving false information to its antennas, enabling the control of its trajectory. Disturbingly, this approach is so trivial and efficient that it can be done by anyone. The American company *Backyard Brains* sells "educational DIY cockroach cyborg kit" with a step-by-step procedure of the implementation. Similar to the backpack concept, here we connect 3 wires inside the insect. One for each antenna (Figure 2a) and another one in the thoracic muscle (Figure 2b) to serve as ground and close the circuit (so the current can flow through the system) [4].



(a) Wire in antenna (b) Wire in thorax

Fig. 2: Wire implementation procedure (a) Wire in antenna (b) Wire in thorax . Figures from [4]

III. Early Metamorphosis Insertion Technology (EMIT)

Recent advancements in bioengineering have enabled the integration of micro-implants into insects before or during metamorphosis. The larval and pupal stages provide ideal windows for insertion, as the wounds heal more effectively, and probes can form stable, reliable structures as tissues grow around them. Unlike adult insects, those in these earlier stages exhibit no adverse reactions to the electronics. This seamless integration facilitates the development of hybrid insect-machine systems, enabling advanced behavioral research [5] and precise flight navigation applications [6].

A. Neurocybernetic implants

The study [6] demonstrated on-demand wing actuation and precise flight direction control using polyimide thin-film-based microprobes inserted via the EMIT procedure at late pupal stage (see Figure 3). These flexible microprobes facilitate high-resolution recording of neural and muscular activity while enabling direct stimulation of tissues, such as activating specific neural circuits or inducing muscle contractions. Their flexibility ensures seamless integration during metamorphosis, making them ideal for exploring insect development, behavior, and bio-hybrid applications.

B. Sustained delivery of bioactive compounds during tissue development

Implanting microfluidic devices during the immature stage of insects offers several advantages, including better integration and adaptation of the devices as the insects develop, resulting in higher survivability rates of 96% (as studied in [6]). This timing ensures that the devices can influence metabolic processes early on, effectively modulating critical compounds like L-glutamic and L-aspartic acids, which are essential for flight metabolism. Additionally, early implantation allows insects to adapt to the changes induced by the microfluidics, achieving a flight-capable rate of 36% post-emergence. The immature stage is also less energetically demanding, enabling

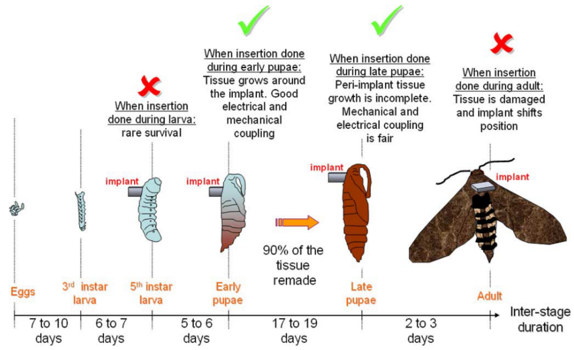


Fig. 3: Life span of Manduca sexta during the metamorphic development and the results of device insertions at various stages of metamorphosis. Figure from [6]

insects to acclimate to the devices without the immediate stress of adult flight.

IV. Biohybrid insect robot interfaces

A. Introduction to biohybrids

New robots are now expected to be small, stretchable, squeezable, agile, and even capable of growing. They are designed for diverse applications, including environmental monitoring, search and rescue, neuroscience, behavioral studies, and agriculture. Advances in fabrication techniques and the miniaturization of electronic controllers and sensors have already enabled the creation of controllable robots as small as insects.

However, the development of new robots still faces challenges due to the size, weight, and stiffness of components. For example, while soft actuators are suitable for handling delicate micro-objects, no existing actuator matches the performance of living muscle tissue. This has made living muscle tissue an area of interest as a potential microactuator. Several bio-actuators using mammalian cells have been developed, but these devices require precise environmental conditions to maintain the muscles' contractile ability, and the medium needs regular replacement. [7] [8]

B. A promising new bio-actuator

Insect tissues exhibit remarkable resilience, thriving in extreme conditions such as temperatures from below 0°C to nearly 55°C, pH ranges of 4 to 11, varying osmolarities, and low oxygen pressures. These tissues, capable of surviving hypoxia for days and withstanding high radiation doses, have inspired biohybrid actuators using self-contractile dorsal vessel tissues (DVTs), comparable to mammalian cardiac tissues. A notable example is a biohybrid micro swimming robot powered by the autonomous contractions of insect dorsal vessel (DV) tissue. The robot, designed with a fish-like anatomy, features a head, hinge, and tail fin, and is fabricated using polydimethylsiloxane (PDMS) for flexibility. Measuring 8.06 mm in length and 2.3 mm in width, with a hinge thickness

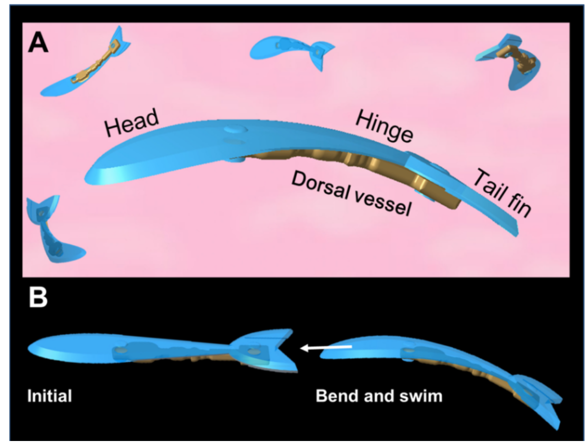


Fig. 4: A) Schematic views of an insect muscular tissue-powered swimming robot.Figure from [9]

of 0.05 mm, the robot's motion is driven by the deformation of the tail fin when the DV contracts. The DV tissue, excised from inchworm larvae (*Ctenoplusia agnate*), exhibits contractile forces from 42.7 µN to 79.6 µN. The robot achieves an actual swimming speed of 11.7 µm/s, with a theoretical maximum of 44.7 µm/s. Fabrication involves PDMS molding via stereolithography, with DV tissue attached under sterile conditions. It operates robustly at room temperature for up to 90 days without requiring medium replacement. [9]

C. Biohybrid Fly-Robot Interface System

This study presents the development of a biohybrid system combining a blowfly's neuronal activity with a robotic platform to study sensorimotor control mechanisms. The system uses the neuronal spiking activity of the H1-cell, a motion-sensitive interneuron in the blowfly, to navigate and perform collision avoidance tasks. The biohybrid Fly-Robot Interface (FRI) consists of a two-wheeled robot with a miniaturized recording platform that monitors the H1-cell activity of a dissected blowfly mounted on the robot. The dissection consist of removing the legs and the wings and to attach the head and body to the fly holder using bee wax.

Under closed-loop conditions, the robot used the H1-cell's activity to detect proximity to walls and trigger avoidance maneuvers, achieving a 90% success rate in wall navigation and 100% success in avoiding 90° corners, though it struggled with acute angles (60°). The study found that the H1-cell's spike rate was proportional to the distance from obstacles within a certain range, enabling reliable collision avoidance. This work demonstrates the potential of biohybrid systems to inform energy-efficient robotic navigation by leveraging biological sensorimotor integration. [10]

V. Ethical considerations

The biggest difference noticed in insect interfaces compared to mammalian ones, is ethical regard. Experiences done with insects population currently lead to rising numbers of subjects death [11]. Besides, it is difficult to imagine a laboratory working on controlling the movements of mice, that would not be well received by the public. Nevertheless, numerous insect studies control their motion. Legally speaking, most countries have strict guideline for vertebrate animals, but insects either are not clearly included or clearly excluded by the framework. Several countries started discussions to insert guidelines for insect testing, debating about their pain perception. In any case, those guidelines are mostly aimed at professional scientific work and would likely only depend on the person's ethical choices. This then raises multiple questions, should insects be treated more humanly by scientists ? Should those experiments only be made in a pro-ecosystem context that would benefit their species ? Like inducing pollination of a certain plant, for example. And finally, should unsupervised experiments on insects be more regulated or even forbidden ? [12]

VI. Conclusion

The integration of biological and technological systems through biohybrid insect interfaces represents a transformative frontier in robotics, bioengineering, and neuroscience. This review has highlighted the key advancements in controlling insect motion, utilizing innovative techniques such as electrical muscle stimulation, neurostimulation, and early metamorphosis implantation technology (EMIT). These developments enable precise behavioral modulation, creating opportunities in applications ranging from search-and-rescue operations to environmental monitoring and agricultural enhancement.

Emerging biohybrid technologies, such as insect-powered actuators and biohybrid robot systems, demonstrate the potential to overcome challenges faced by traditional robotics. Leveraging the unique properties of insect tissues, these systems achieve unparalleled efficiency, adaptability, and resilience under extreme conditions, pushing the boundaries of miniaturization and performance (10 to 100 times longer operational time).

However, the rapid progress in this field necessitates thoughtful consideration of ethical implications. The current lack of stringent regulatory frameworks for insect experimentation contrasts with the growing capabilities to manipulate their behavior. This underscores the need for an ethical framework that balances innovation with respect for biological integrity.

In conclusion, biohybrid insect systems exemplify the convergence of biology and engineering, offering revolutionary solutions across diverse domains. As the field matures, it will be crucial to foster ethical practices and sustainable applications to harness the full potential of these remarkable technologies responsibly.

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