# EE-519 Bioelec Insect Interfaces Project

Jintian Yang
*Biomedical Engineering*
*EPFL*

Mona Victoria Vahedi
*MsC Cybernetics and Robotics;*
*Biomedical Cybernetics*
*EPFL*

Trisha Chari
*Electrical and Electronics Engineering*
*EPFL*

***Abstract*—Recent advancements in micro fabrication, miniaturization of electronics and the development of low power wireless systems have enabled the development of insect interfaces. The interfaces make use of the insects' natural locomotion abilities, energy efficiency, and specialized sensory- and motor systems to achieve results that are challenging to reproduce in conventional robotic platforms. These systems are capable of tracking and controlling insect behavior, by adding external stimulation to interfere with the insect's organic control loop. This report aims to give an overview of the biological foundations that make insects suitable for neuromuscular intervention, the historical progression from early passive radio telemetric systems to modern programmable control systems, technologies and methods for wireless electronic integration, electrode design and behavioral control strategies used today for free flight control. Finally, the report discusses the main challenges and the limitations that must be addressed for future applications.**

## I. INTRODUCTION

Recent advancements in reducing hardware component sizes, improvements in micro fabrication techniques and the development of power efficient radio systems has enabled the creation of insect interfaces that allow tracking and motion control of insects [1] [2]. Remotely controlling insects provide several benefits. Firstly, it enables the studies of insect behavior, such as their communication and mating practices, as well as observing their predators. For several years, flying insects maneuverability, stealth and ability to operate energy efficiently, has led to the development of insect mimicking micro- and nano air vehicles (M/NAVs) [3]. Specifically, flapping-wing MAVs have attracted big interest because of their reduced energy utilization and cost benefits over aircraft with fixed and rotary wings. Other important characteristics of insects that have made an important study object for flying wing MAVs, is their small size and weight, low noise and hoverability [3]. Their small scale signifies a low Reynolds number, indicating that their flight is dominated by viscous forces instead of internal forces. This means that they swim through the air instead of flying in a conventional sense [4]. The scale of insects and their adaptations to certain conditions can thus allow them to explore environments that are inaccessible for humans or mobile robots.

Another important factor that draws the attention to the study of insects is that they provide a readily accessible interface for examining the combination of living organisms and man-made machines in the execution of complicated tasks [2]. Although machine-organism interfaces assumably wouldn't replace the production of fully robotic systems, the research can eventually unlock a new class of programmable machines [2].

## II. BACKGROUND

### A. Biological Foundations for Intervention

Insects exhibit several key characteristics that make them particularly suitable as engineering platforms. First, their neurophysiology provides a basis for control. Integrating a synthetic control into the existing biological control loop is a fundamental concept for insect interfaces [2]. Correctional schemes during free flight involve directly stimulating large and easily reachable muscles, directly stimulating a larger group of neurons in a ganglion, and targeted stimulation of nerves in a nerve cord [5].

The stimulation of certain anatomical targets have been proven to be successful. For instance, the initiation and cessation of flight can be achieved by applying electrical pulses to implanted electrodes at the base of the optic lobes [2]. In similar matter, directed turns in flying beetles have been evoked by stimulating the right and left basalar muscles [2].

A further advantage lies in the insects that undergo full metamorphosis. Implanting foreign objects during the pupal stage can result in a mechanically robust interface, as the developing cuticle hardens around the implant [5]. To summarize, insects provide a preexisting, efficient organic control system that can be modified through external intervention. Furthermore, implantation during the pupal stage of the insect allows for the stable integration of hardware, providing durability for the system.

### B. Historical Development of Insect Telemetry

The evolution of insect interfaces can be dated back to simple tracking tags from the 1980s, and has advanced to modern control systems [1]. The progression is mainly enabled by the miniaturization of electronics. A pioneering study featuring radio telemetry with insects (with telemetry meaning exchanging data from a remote to a centralized point for monitoring and analysis), examined the movement patterns and foraging of the dobsonfly larvae [1]. However, the initial instruments were technologically constrained. The devices employed tailored radio components assembled from surface mount devices and lacked integrated memory, digital processing, and programmability, making them no more advanced than a simple transmitting tracker [5]. Since then, radio telemetric systems have advanced, yet face limitations when trying to design a transmitter that simultaneously exhibits low weight, power efficiency, and long battery life [1]. Today, the weights of the most basic radio transmitters for vertebrates have been reduced to less than 5 g, with transmitters weighing below 1 g now available [1]. Overcoming the weight barrier enabled the transition from passive telemetry to modern programmable control systems.

## III. TECHNOLOGIES AND METHODS

### A. Introduction to wireless miniature electronic technology

Embedding electronics into insects requires small and lightweight interfaces which integrate seamlessly with an insect's muscular and neural system. This section explores the specific technologies required to achieve flight control and data collection from insect interface technologies.

### B. Neural and Muscular interface technologies

The technology required to implement an electrode onto a muscular or neural surface on an insect to actuate flight control successfully must satisfy extremely specific conditions.

*1) Functional success criteria:* Firstly, stimulation with **multiple data transmission channels** can greatly improve data resolution, transmission speeds and complexity of functions such as voltage regulation and feedback control. **On-board digital processing** enables recorded audio and video to undergo noise filtering and incorporate feedback for a better control system, and dynamically readjust amplification or filtering parameters when electrodes shift over time (Electrode Drift). This is advantageous compared to filtering signals and data post-retrieval. **Memory** is another integral feature for the storage of experimental video and audio-related results. Additionally, **programmability**, achieved using micro-controllers on-board the chip, enables autonomous functions and smart features to elevate the quality of measurements.

*2) Limitations:* The **weight** of the device must be regulated to not hinder the free flight of an insect. Furthermore, **power efficiency** is an important factor that can prolong flight time to collect data. **Flexible and implantable** systems also mean robustness and structural integrity when interfaced with an insect. The more physically and chemically immune to damage the device is, the more reliable data collected will be.

### C. Electrode mechanisms

Electrodes are part of the bio-electronic technology, which must be carefully configured to interface with the muscular and neural system of insects.

*1) Tissues:* Interfacing with the insects' system can be done via muscles or the neural system. Flight control muscles, such as the direct flight muscles known as basalar muscles on insects, can control steering, turning and major flight movements by triggering the major wing muscle [**?**]. They cover a large surface area and hence create a more stable connection to an electrode [1]. Indirect flight muscles may also be controlled, summarized in Figure 1, which controls the movements near the thorax to control the wings' upstrokes and downstrokes.

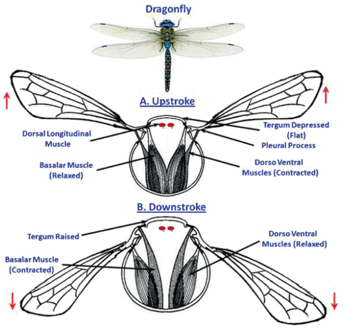

Fig. 1. Direct and Indirect muscle stimulation. From [**?**].

On the other hand, nervous system tissues such as the brain, antennae and ganglia [6] can be attached onto electrodes to control reflexes and sensory control.

Targeting muscles can tolerate better electrical stimulation compared to targeting neurons when interfacing with an insect's anatomy.

*2) Electrode technology:* **The Flexible Split-ring Electrode (FSE)** has two layers of polyimide with gold in between on a split ring [7]. Its advantage is that it is flexible to easily attach onto nerves and can also transmit information via wireless telemetry. Both the stimulation and telemetry system are shown in Figure 2, which is taken from Tsang (2010).

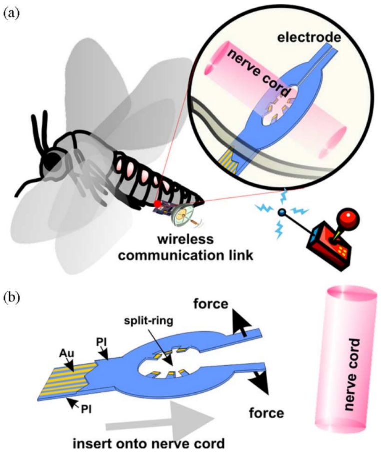

Fig. 2. Flexible Split-ring Electrode Implementation and Telemetry. From [7].

**Dual-side micro-electrode arrays** are flexible micro-electrodes with pads on both sides, allowing two-sided contact with tissues or muscles. This offers stability and easy access to brain tissue and enables high-density recording [8].

Furthermore, **Tungsten wire electrodes** are also used by inserting a polyimide-coated tungsten wire into the cerci of an animal and a reference electrode into the second abdomen and securing it with beeswax [6], as seen in Figure 3. Tungsten is used for its high melting point, conductivity and corrosion resistance over prolonged periods of use [9].

*3) Electrode technological developments:* A range of technological developments outlined below, showcase different

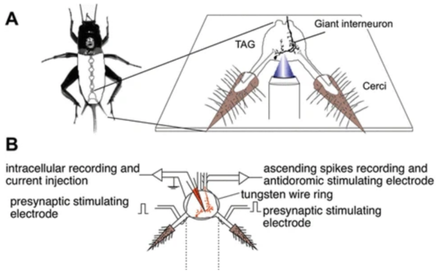

Fig. 3. Tungsten electrode insertion into cockroach. From [9].

factors and features being prioritized to achieve different goals in implantable biotechnology. **In 1993, Kutsch et al** contributed to one of the first inventions in the insect interfaces field. It comprised a 0.42g Telemetry backpack for a locust, which utilized a mono-channel transmitter to acquire Electromyograms (EMG) for one flight muscle of interest. **In 1999, Fischer and Ebert** developed a 0.23g dual-channel backpack which could compare EMGs from the flight muscles, especially tested on male hawk-moths for zig-zag triggered flight. **In 2009, Sato et al.** used an 8-channel CC2431 micro-controller with a built-in transceiver with ceramic surface-mount components, focussing on reducing size and mass, and hence the external effect on a flying insect. **Also in 2009, Bozkurt et al** developed a two-channel AM receiver using pulse-position modulation (PPM) which was also fed into a micro-controller. **In 2009-2010, Daly et al** developed a custom silicon System on Chip (SoC) receiver utilising an MP340 micro-controller, with a 2.5mW low-power operation. This was a breakthrough in low-power technologies for implantable devices.

An example of the electrical schematic design, considering the small size of the ”backpack”-implant approach, is shown in Figure 4. It incorporates an STM32 Microcontroller, 4 individually controllable channels and 16-bit DAC with I2C communication [6].

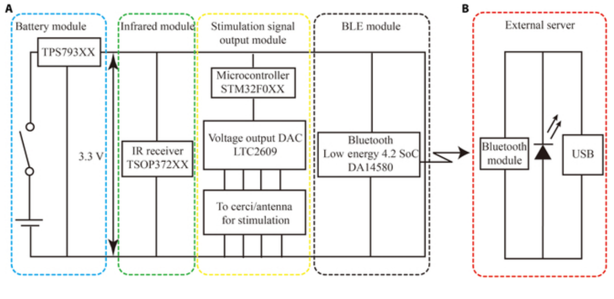

Fig. 4. Schematic of a cockroach wireless control backpack. From [6].

### D. Methods of Behavioral control

The methods devised to control flight rely on an insect's ability to fly freely, due to their rapid wing movements and navigational abilities, which cannot be mirrored at such a small scale by electronics. The devices' purpose is to simply influence the free flight trajectory to exercise control over the insect's decisions, rather than to reprogram their physiological movements. Hence, as shown, an electronic implantable device with three degrees of freedom allows for this control. **Flight initiation** and commencement is able to be controlled using positive and negative pulses at 100Hz between the left and right lobes. This triggers wing oscillations and the ability to control flight [10]. A study according to Jadhav, Maharbiz and Sato (2014) showed results on stimulating the optic lobes and light receptors of the Mecynorhina Ugandensis beetle. Usually, the neural activity in the optic lobes of the beetle decreases, causing flight to cease after dusk. It was found that applying a 50ms period pulse train to the Basalar muscles on the optic nerves could re-stimulate the insect to re-initiate flight, and do so with the same capability.

**Flight cessation** is caused by using single pulses instead, which is found to stop wing oscillations. In order to control **turning**, pulse trains at 100Hz at 1.3V potential could be applied to the respective left or right Basalar muscle [10]. The **pitch and elevation** of the flight of an insect was found to be altered by alternating positive and negative pulse trains at a 2V amplitude. Similarly, **throttling** could be achieved by increasing the frequency of the pulse train sent to the Basalar muscles [2].

## IV. CHALLENGES

Despite significant advances in insect interfaces, the integration of electronic systems and insects faces various challenges. These challenges arise from inherent trade-offs within electronic components, constraints imposed by biological platforms, and bidirectional incompatibilities at the bio-electronic interface. Understanding these limitations is critical for interface development and its further application.

### A. Electronic System Constraints

Miniaturization of insect interface electronics is constrained by inherent trade-offs between competing performance requirements. The primary limitation is the inverse relationship between device size and power capacity: reducing mass to minimize burden on the insect directly reduces battery volume, which in turn limits both operational lifespan and available power for stimulation or transmission [1]. This size-power constraint manifests in multiple ways. Extending control range requires larger antennas and higher transmission power, yet these directly conflict with the weight minimization necessary to preserve natural locomotion [1]. Similarly, integrating additional functionality, such as multi-channel stimulation or environmental sensors—demands more components and power, forcing designers to sacrifice either capability or miniaturization. Beyond these fundamental trade-offs, fabrication scalability poses another challenge, as many existing insect interfaces rely on time-intensive manual fabrication of small electronic payloads and surgical implantation procedures, precluding mass production for large-scale deployments [11].

### B. Biological System Constraints

The biological platform imposes inherent limitations independent of electronic integration. First, neural connectivity patterns remain incompletely mapped for most insect species, making it difficult to predict which brain regions control specific behaviors and resulting in unaccountable variability in stimulation outcomes [11]. Beyond neural uncertainty, anatomical differences across species and even individuals constrain electrode placement precision, as the location and accessibility of target neural structures vary by hundreds of micrometers [12]. Additionally, Natural behavioral variability introduces unpredictability into command responses, with control reliability degrading significantly when insects are guided into environments they instinctively avoid, such as bright or cold areas for cockroaches [13]. These biological constraints fundamentally limit the degree of control achievable regardless of electronic sophistication.

### *C. Bidirectional interaction*

The integration of biological and electronic systems produces bidirectional interference: biological responses degrade electronic performance, while electronic components impose physiological costs on the organism. On the one hand, biological responses progressively degrade electronic performance. Prominently, neuroplasticity reduces stimulation efficacy as neural circuits habituate to repeated activation. For example, cockroach turning responses decrease with prolonged stimulation and need rest periods to recover [14]. At the physical interface, electrode performance deteriorates through multiple concurrent mechanisms: electrode shifting due to tissue remodeling, fibrous encapsulation driven by foreign body responses, and corrosion from the ionic environment, all of which increase impedance and reduce signal quality over time [15].

On the other hand, electronic integration imposes physiological costs on the organism. Temporally, implantation timing affects survival and organ development. For example, devices implanted during pupal stages risk disrupting metamorphosis despite enabling better neural integration [5]. Physically, electronic integration degrades both locomotor performance and even tissue health: device burden increases energetic costs and impairs flight maneuverability through added mass and drag [5], while chronic electrical stimulation causes localized tissue damage that triggers inflammatory responses, thus even worsening the bio-electronic interface over time. Behaviorally, device protrusions alter natural movement patterns unpredictably; for instance, beetles with dorsal-mounted electronics become trapped by obstacles such as twigs that unmodified individuals navigate easily [1]. These cumulative physiological costs reduce both animal welfare and the reliability of experimental data.

## V. CONCLUSION

### *A. Future implications*

Future research must address key limitations including the power-size trade-off [1], biocompatibility issues [5], neuroplastic habituation [14] and incomplete neural connectivity mapping [11]. Advances in electrode materials and design, and deeper biological knowledge could help overcome these obstacles. Successfully addressing these challenges would enable practical applications in search and rescue operations and more reliable environmental monitoring.

Overall, the development of bio-technology is evolving to continue to fabricate chips and structures that can make better trade-offs between performance and size and weight. The wealth of future implications for insect interfaces will be aided by the increase of miniaturized bio-technology.

## ACKNOWLEDGMENT

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