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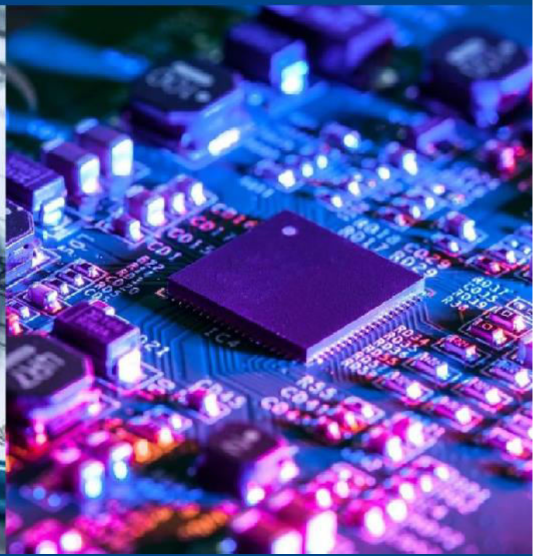

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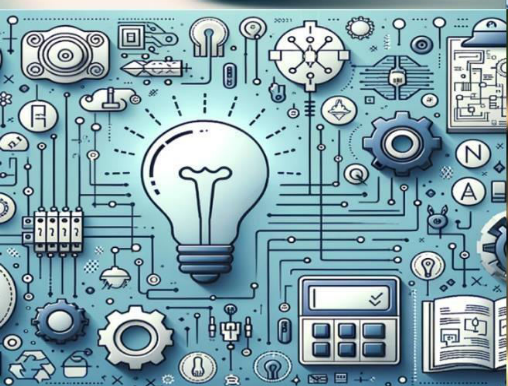

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Solar-Powered Cyborg Insects: A Breakthrough in Energy Harvesting for Robotics

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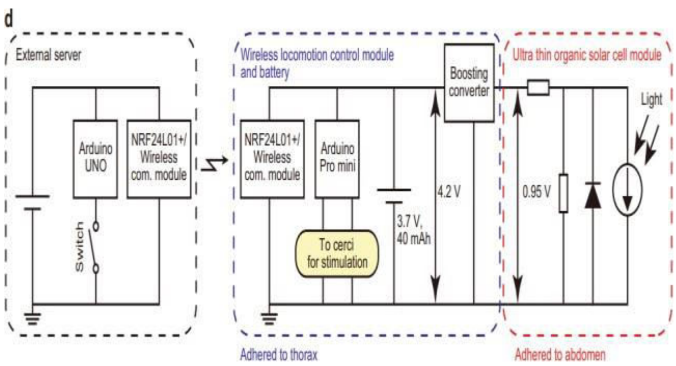
ABSTRACT: This study demonstrates the development of a cyborg insect equipped with an ultrasoft organic solar cell module designed to recharge its battery while preserving its basic motion abilities. The integration of ultrathin film electronics, mounted on the insect's abdomen using an adhesive- non-adhesive structure, ensures that the insect can self-right and maintain fundamental mobility. Thesolarcellmodule achieved a power output of 17.2 mW, enabling the successful wireless control of the insect's locomotion after recharging. The design strategy, focusing on minimizing the impact on the insect's natural movement, highlights the potential for practical applications of cyborg insects in fields like search and rescue.

I. INTRODUCTION

Advancements in electronics and miniaturization have enabled the integration of small, low-power semiconducting chips into organisms, creating cyborg insects capable of performing tasks like search and rescue, environmental monitoring, and hazardous area inspection. Stretchable electronics, designed to seamlessly fit on curved insect bodies, have made this possible without impairing their mobility. One of the biggest challenges has been finding efficient power sources that don't limit the insect's movement. Traditional batteries are too bulky, but alternative energy-harvesting methods, like biofuel and solar cells, have emerged as viable solutions. Ultrathin organic solar cells, in particular, have shown promise, providing high power output while maintaining the insect's natural motion.

A new design of ultrasoft organic solar cells, mounted on cyborg insects, has achieved a power output of17.2mW and enabled wireless locomotion control without hindering the insect's basic abilities. This breakthrough allows cyborg insects to operate autonomously and untethered for extended periods. The successful integration of flexible energy-harvesting devices ensures that these insects can perform tasks efficiently in environments where traditional robots or humans would struggle. As technology improves, cyborg insects may become indispensable for applications in extreme or inaccessible conditions.

A. Architecture



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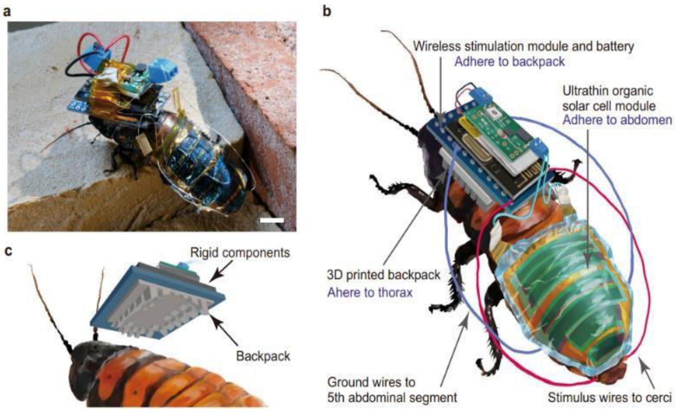
B. Prototype

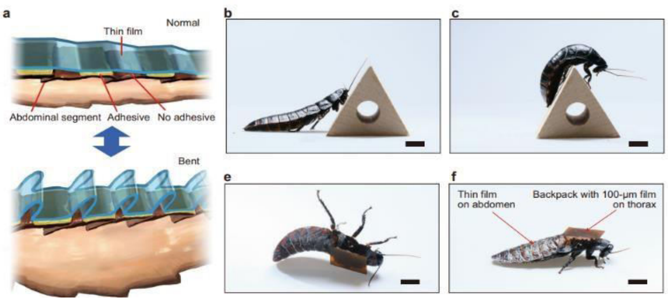


II. STRUCTURE OF THE RECHARGEABLE CYBORG INSEC

In this study, **Gromphadorhina portentosa** (Madagascar hissing cockroach) was selected as the cyborg insect model. Various electronic components, including a **wireless locomotion control module**, were mounted on the insect's dorsal side. This control module consisted of **wireless communication circuits**, **stimulation voltage controller circuits**, **boosting circuits**, and a **lithium-polymer battery**. These components were mounted on the thorax using a **3D-printed soft backpack** that followed the curved shape of the insect's body, ensuring stable and long term adhesion.A **4µm thick organic solar cell** was attached to the insect's abdomen. When exposed to **simulated sunlight** (100 mW/cm²), the solar cell generated power, which was boosted to **4.2V** to charge the battery. The battery then supplied power to the wireless locomotion control module. **Locomotion signals**

were transmitted wirelessly via **Bluetooth** from an external server to stimulate the insect's cerci (paired appendages at the rear of the abdomen).When electrical stimulation was applied to the **right cercus**, the insect turned right, and vice versa.

The soft backpack, 3D-printed from elastic polymer, was designed using a **precise 3D model of G. portentosa** to ensure a snug fit, providing stability and maintaining adhesion over extended periods, even in a breeding environment. This design prevented issues such as **delamination**, which occurred when traditional adhesives like beeswax were used.



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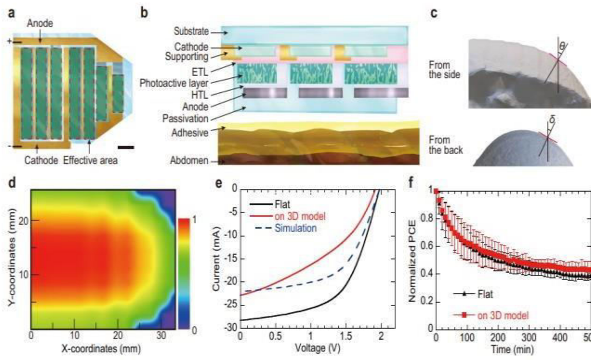
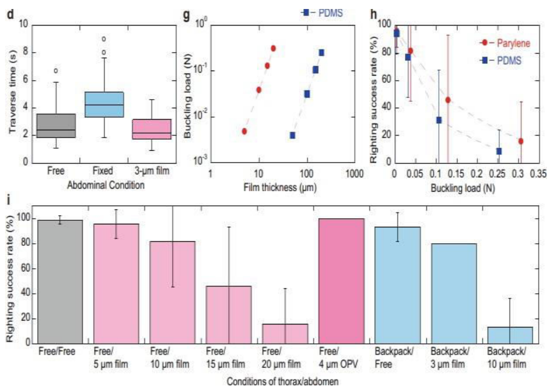


Fundamental behavioral ability with electronics:

The study carefully examined how integrating thin-film electronics onto cyborg insects impacts their mobility and self-righting abilities, focusing on the balance between maintaining natural movement and supporting the electronic components needed for cyborg functions. By using an adhesive-non adhesive interleaving structure, thin-film electronics were attached to the insect's abdomen in a way that allowed the films to bend outward during movement, preserving the insect's flexibility. This innovative structure ensured that the insect's mobility was largely unaffected, even when electronics were added. Tests revealed that when **3µm parylene films** were used, the insect's ability to traverse obstacles was nearly identical to that of insects without any films. The traversal times, a key measure of movement efficiency, remained comparable, indicating that the thin films did not significantly hinder their locomotion.

However, the study also found that as the **thickness of the films increased**, the insect's ability to perform complex Movements like self-righting was negatively impacted. Thicker films required a greater buckling load, meaning more force was needed to bend them during movement. This made it harder for the insect to restore itself to an upright position when flipped, reducing the **self-righting success rate**. A comparison between parylene and PDMS films showed that thinner films—whether parylene or PDMS—consistently supportedbettermobilityandself-rightingperformance.Thestudyconcludedthatoptimizingthedesignbycombining soft, flexible films on the insect's abdomen, which allowed for natural movement, with more rigid components on the thorax, where flexibility is less critical, provided the most effective integration of electronics without compromising the insect's natural abilities. This balance of rigidity and flexibility is essential for maintaining the insect's functional capabilities while enabling the additional technological enhancements required for cyborg applications.



III. MOTION ABILITY OF INSECTS WITH THIN FILMS

A comprehensive design strategy was devised to attach ultrathin films to the abdomen of insects in a way that preserves their natural movement and agility. This strategy employed an **adhesive–nonadhesive** interleaving structure, which allowed the films to bend flexibly during abdominal deformations, preventing any restrictions on segment overlap or movement. The films were designed to accommodate the insect's body dynamics, particularly when bending or twisting. Testing showed that insects fitted with a **3 µm thick film maintained** mobility almost identical to unmodified insects.

This preservation of mobility was critical, as it demonstrated that the thin-film design did not impede basic locomotion or agility. However, as film thickness increased, the insects experienced more difficulty in movement, particularly in performing self-righting actions, where they flipped back on to their feet after being overturned. The righting success rates were significantly affected by film thickness, **ranging from 96% for the thinnest films down to 16% for the thickest ones.** Films around 5 µm provided the optimal balance, allowing the insects to retain most of their movement capabilities.

The study also explored the relationship between film thickness, buckling load (the force needed to bend the films), and the **insects'self-righting abilities**. It was found that films requiring a buckling load **of less than 0.05N** correlated with an 80% success rate for self-righting attempts, highlighting the importance of maintaining a low resistance to bending. The

Integration of ultrathin electronic components, such as organic solar cells, was particularly noteworthy. These components were attached without causing any adverse effect on the insects' movement. In fact, with the ultrathin electronics, the insects achieved a 100% success rate in self-righting, proving that such components can be seamlessly integrated without hindering mobility. In contrast, thicker films attached in different configurations had a minor, but measurable, impact on mobility, showing the importance of film thickness and design in ensuring that the insects retain their natural abilities even when equipped with advanced electronic systems.

Performance of ultrathin organic solar cell module

The ultrathin organic solar cell module tailored for the curved abdomen of G. portentosa demonstrates a notable power output of upto17.2mW.This performance is achieved by optimizing both the surface area coverage and the angle of light incidence. Specifically, the module encompasses 51% of the abdominal area, configured in a three-series connection to enhance efficiency. When tested on a flat surface, the module delivered 31.5 mW; however, this output decreased to 17.2 mW on the curved surface, primarily due to a reduction in light intensity caused by the angle of incidence.

The diminished performance on curved surfaces can be attributed to several factors. Increased leakage current and shunt resistance are significant contributors, leading to a power density of 4.34 mW/cm^2, which is lower than that of flexible organic solar cells.

To address these challenges, future enhancements could focus on material improvements, design optimization, and strategies to mitigate angle-dependent efficiency losses.

Stability assessments revealed that the module maintains consistent performance on both flat and curved surfaces. Nonetheless, larger modules exhibited accelerated degradation, likely due to the presence of leakage paths. Addressing these degradation mechanisms is essential for the development of durable, high-efficiency ultrathin organic solar cells suitable for practical applications.

IV. CHARGING WIRELESS LOCOMOTION CONTROL SYSTEM OF LIVING CYBORG INSECT

The study introduced a novel strategy for integrating electronics onto insects, specifically **Gromphadorhina portentosa**, to achieve wireless locomotion control and efficient energy harvesting. At the core of this innovation was the use of an ultrathin organic solar cell module, which provided sufficient power to charge a lithium–polymer battery. The solar module utilized a boosting converter to elevate the voltage **from 0.95 V to 4.2 V**, effectively poweringtheinsect'smovementcontrolsystem.Afterjust30 minutes of exposure to simulated sunlight, the battery was fully charged, enabling **wireless control of the insect's movements for 2.1 minutes**. The design employed soft, flexible electronics, ensuring that the module did not hinder the insect’s natural locomotion. The unique adhesive–nonadhesive interleaving structure between the thorax and abdomen allowed freedom of movement, further enhancing the insect's mobility even while equipped with electronic components. This structural innovation was critical, as it maintained the insect's normal behavior while providing the necessary technological enhancements for remote control.

Moreover, the adaptability of the soft, flexible electronics makes this approach scalable to other insect species, significantly broadening its potential applications. The study identified key areas for future improvement, including the reduction of circuit size and weight to further minimize interference with the insect's motion. Additionally, optimizing

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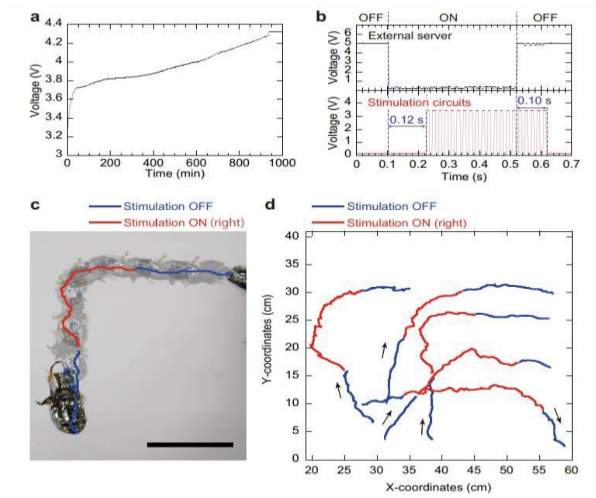
the power generation capabilities of the solar cell through design improvements—such as **integrating nano- grating structures or using advanced materials—could enhance energy efficiency** and extend operational duration. This innovative approach holds promise for a wide range of applications, from environmental monitoring and disaster relief to search and rescue missions, where untethered cyborg insects could operate autonomously in challenging environments that are difficult for traditional robots or humans to access.



V. 3D MODEL OF G.PORTENTOSA

A frozen G. portentosa female was placed on a small turntable, and 45 images were captured by rotating the specimen at 8° intervals. The images were imported into photogrammetry software **(3DF Zephyr, OPT Technologies)** to create a precise 3D model.

VI. ABDOMINAL SHAPE MEASUREMENT

An adhesive elastomer sheet (Y-4905J, 3 M ™) was tightly attached to the abdomen of a female G. portentosa specimen to fill the abdominal area. A paper was attached to the elastomer sheets to prevent deformation during delamination. The shape was determined with delaminated elastomer sheets and then approximated to a pentagon with a **total area of 777 mm^2 .**

VII. CONFIRMATION OF THE ABDOMINAL MOVEMENT AND SEGMENT SHAPE

Cross-sectional observation was performed to confirm the movement of the abdomen of G.portentosa.With a specimen Frozenat–18°C,a CO_2 laser processing machine(FABOOL Laser CO2, Smart DIYs Inc.) was used to cut G. portentosa from the centre of the thorax to the abdomen. Observations were conducted using a microscope (Dino-Lite Edge, Opto Science).The range of movement was measured using cross- sectional observation. The abdomen was disassembled into segments to measure the segment depth, width, thickness, and radius of curvature.

Design and fabrication of backpack

To achieve stable adhesion of rigid components on the thorax, the backpack was designed to cover the first to third thoracic segments of the 3D model of G. portentosa. The backpack was fabricated using a **stereolithography 3D printer (Form3, Formlabs)** with an elastic polymer (Elastic 50 A, Formlabs).The interface between the backpack and the insect surface was divided into columns. The columnar structures were attached to the first to third thoracic segments using a superglue(LOCTITE,LBR-005).Thanks to the softness and columnar structure, the backpack adhered to different individuals appropriately, confirming the adequate integration of circuits onto the **G. portentosa species**.

Attaching thin films to the abdomen

A **resin-based adhesive** for the skin (Spirit Gum, Mitsuyoshi) was evenly applied to the abdomen, and a thin film was

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attached to the surface of the insect. The adhesive was liquid and exhibited some adhesive strength even before curing. During the curing of the adhesive, the part of the adhesive where the segments overlapped was scraped off by the natural movement of the insects, which resulted in an **adhesive–nonadhesive** interleaving hollow structure.

Self-righting attempts

G. portentosa was held in an upside-down orientation and then released on the ground covered with recycled paper. If the animal righted from an upside-down orientation **within 60 s**, the case was considered to be **a success**. The same attempts were repeatedly conducted with various individuals and film/component conditions on both the abdomen and thorax.Wecollectedfromatotalofatleast3individualswith at least 5 trials from each individual for each condition.

Charging test

The lithium–polymer battery was discharged to **3.2 V** using an electrochemical measurement system (HZ-7000, Hokuto Denko). The **organic solar cell module** attached to the 3D printed G. portentosa model was connected to the battery. The simulated 1-Sun light was applied continuously to the module directly from above, and the voltage between the batteries was monitored using **a source meter (Series2400, Keithley)**.

VIII. ACKNOWLEDGMENTS

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