Scientists develop technology to control cyborg insect swarms

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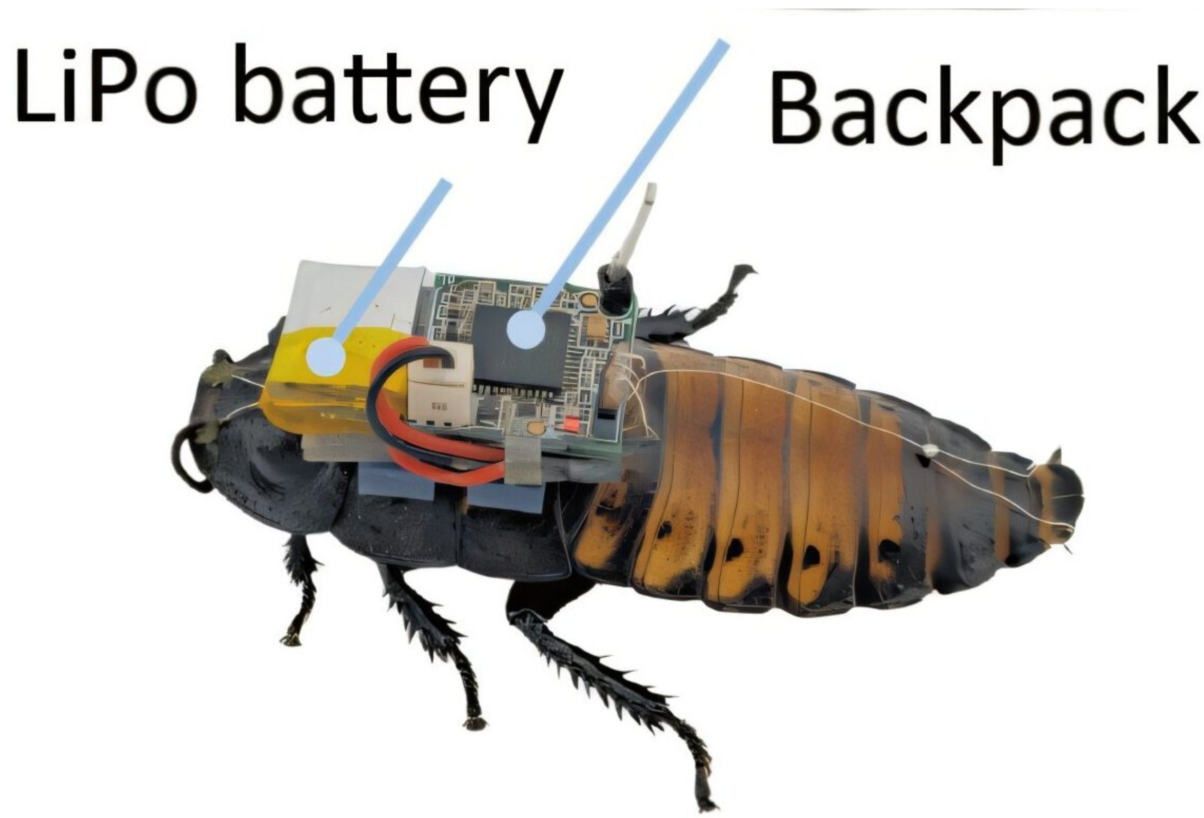

Electronic "backpack" that will navigate the cyborg insect to its intended destination or objective. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-024-55197-8

Scientists have developed an advanced swarm navigation algorithm for cyborg insects that prevents them from becoming stuck while navigating challenging terrain.

Published in *Nature Communications*, the new algorithm represents a significant advance in swarm robotics. It could pave the way for applications in disaster relief, search-and-rescue missions, and infrastructure inspection.

Cyborg insects are real insects equipped with tiny electronic devices on their backs—consisting of various sensors like optical and infrared cameras, a battery, and an antenna for communication—that allow their movements to be remotely controlled for specific tasks.

The control of a single cyborg insect was first demonstrated by Professor Hirotaka Sato from NTU Singapore's School of Mechanical and Aerospace Engineering in 2008.

However, a single insect is insufficient for operations such as search-and-rescue missions, where earthquake survivors are spread out and there is an optimal 72-hour window for locating them.

In 2021 and 2024, Prof Sato and his partners from Singapore's Home Team Science & Technology Agency (HTX) and Klass Engineering and Solutions demonstrated how cyborg insects may be used for search and rescue operations in the future.

This latest paper on the new swarm system uses a leader-follower dynamic, where one cyborg insect acts as a group leader guiding 19 others.

Co-corresponding authors of the paper, Professor Masaki Ogura from Hiroshima University and Professor Wakamiya Naoki from Osaka University, developed the swarm control algorithm and computer programs, while NTU Professor Sato and his team prepared the cyborg insect swarm, implemented the algorithm on the insects' electronic backpacks, and conducted the physical experiments in Singapore.

The scientists noted several benefits to their new swarm algorithm during lab experiments. Allowing the cyborg insects to move more freely reduced the risk of the cyborgs getting stuck in obstacles, and nearby cyborgs could also help free those stuck or flipped over.

How the cyborg insect swarm works

Earlier research demonstrated control of a single cyborg or a group that was controlled by algorithms that provided detailed and complex instructions for individual insects, an approach that would not coordinate movement for a big group.

With the new method, the leader insect is first appointed by the algorithm, then notified of the intended destination, and its control backpack will coordinate with the backpack of others in the group to guide the swarm.

This "tour leader" approach allows the swarm to adapt dynamically, as the insects can assist each other to overcome obstacles, adjusting their movements if one member becomes trapped.

The insects used are Madagascar hissing cockroaches equipped with a lightweight circuit board, sensors and a rechargeable battery on their backs—which forms an autonomous navigation system that helps them navigate their surroundings and nudges them towards a target.

These cyborgs consume significantly less energy than traditional robots, which rely on power-intensive motors for movement. The insect's legs provide the locomotion needed to move the backpack, as the backpack nudges the insect by applying tiny electrical stimulations, guiding it in a particular direction.

When combined with the swarm control algorithm, the insects' instincts enable them to navigate complex terrains and respond rapidly to environmental changes.

In experiments, the new algorithm reduced the need to nudge the insects by about 50% compared to earlier approaches, thus allowing the insects to have more independent navigation over obstacles and resolving issues such as insects becoming stuck or trapped.

Still photo of cyborg insect swarm navigation. The front left insect (nearest to camera) is the leader. Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-024-55197-8

Prof Sato said the technology is envisioned to be helpful in search and rescue missions, infrastructure inspection, and environmental monitoring, where narrow spaces and unpredictable conditions render conventional robots ineffective.

"To conduct search and inspection operations, large areas must be surveyed efficiently, often across challenging and obstacle-laden terrain. The concept involves deploying multiple swarms of cyborg insects to navigate and inspect these obstructed regions. Once the sensors on the backpack of a cyborg insect detect a target, such as humans in search-and-rescue missions or structural defects in infrastructure, they can wirelessly alert the control system," explains Prof Sato.

Prof Sato is renowned for his pioneering work in cyborg insects. He had previously received global recognition when his research was named one of TIME magazine's 50 Best Inventions of 2009 and one of the 10 Emerging Technologies of 2009 (TR10) by MIT Technology Review.

Co-corresponding author of the paper, Professor Masaki Ogura, Graduate School of Advanced Science and Engineering at Hiroshima University, said, "Our swarm control algorithm represents a significant breakthrough in coordinating groups of cyborg insects for complex search-and-rescue missions. This innovation has the potential to greatly enhance disaster response efficiency while also opening new avenues for research in swarm control. It underscores the importance of developing control methods that perform effectively in real-world scenarios, going beyond theoretical models and simulations."

Illustration of how multiple cyborg insects will follow a single leader (swarm navigation). Credit: *Nature Communications* (2025). DOI: 10.1038/s41467-024-55197-8

Co-corresponding author, Professor Wakamiya Naoki, Graduate School of Information Science and Technology, Osaka University, explained, "Unlike robots, insects do not behave as we intend them to. However, instead of forcibly trying to control them precisely, we found that taking a more relaxed and rough approach not only worked better but also led to the natural emergence of complex behaviors, such as cooperative actions, which are challenging to design as algorithms.

"This was a remarkable discovery. While their actions may appear haphazard at first glance, there seems to be a great deal we can still learn from the sophisticated and intricate behaviors of living organisms."

Their latest advance underscores the practical potential of biohybrid systems in addressing real-world challenges and the importance of global interdisciplinary research collaborations.

Looking ahead, the joint team aims to develop algorithms that enable coordinated swarm actions beyond simple movements, such as collaboratively transporting large objects.

They also plan to conduct experiments in outdoor environments, including rubble piles commonly found in disaster zones, to validate the algorithm's effectiveness in more complex and real-world scenarios.

More information: Yang Bai et al, Swarm navigation of cyborg-insects in unknown obstructed soft terrain, *Nature Communications* (2025). DOI: 10.1038/s41467-024-55197-8