How microorganisms without a complex nervous system swim in liquids

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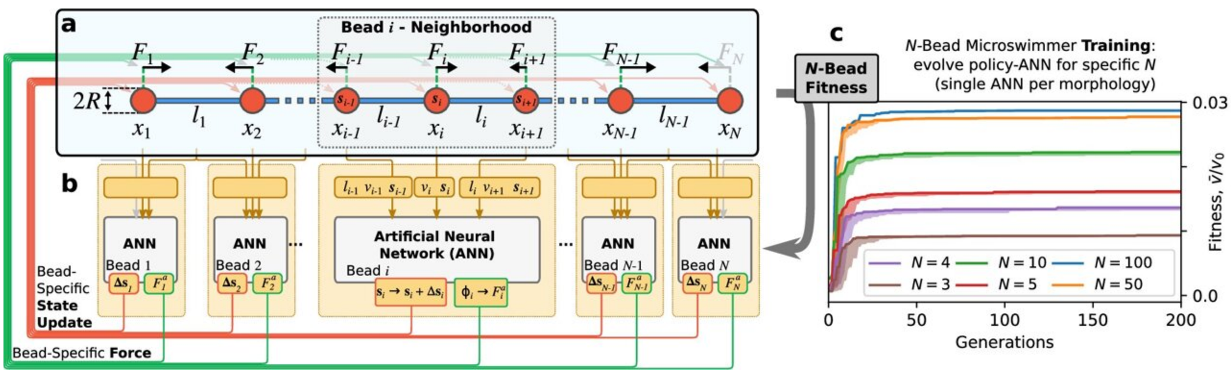

Neuroevolution of decentralized decision-making in N-bead swimmers. Credit: *Communications Physics* (2025). DOI: 10.1038/s42005-025-02101-5

Bacteria can do it, amoebas can do it, even blood cells can do it: They all have the ability to move in a goal-oriented way in liquids. And they do so despite having extremely simple structures without a central control system (such as a brain). How can this be explained?

A team from TU Wien, the University of Vienna, and Tufts University (U.S.) simulated this type of movement on a computer and were able to show that swimming movements are possible even without a central control unit. This not only explains the behavior of microorganisms, it could also enable nanobots to move in a targeted manner, for example to transport drugs to the right place in the body.

Success even without a central control system

"Simple microorganisms can be imagined as being composed of several parts, a bit like a string of pearls," says Benedikt Hartl from the Institute of Theoretical Physics at TU Wien and the Allen Discovery Center at Tufts University, lead author of the current study published in *Communications Physics*.

"The individual parts can move relative to each other. We wanted to know under what circumstances does this result in a movement that causes the entire organism to move in a desired direction?"

This is relatively simple if there is a central control system—something like a brain or at least a nerve center. Such a center can issue specific commands to the individual parts. It is easy to understand how this can result in coordinated movement.

But a single-celled organism naturally has no nerve cells, no central processing system that could issue commands. How is it possible in this case for a coordinated swimming movement to arise? If the individual parts of the microorganism all behave according to very simple rules, can this result in collective behavior that leads to efficient swimming?

Microorganisms simulated on a computer

This question was investigated using computer simulations: the microorganisms were modeled as chains of interconnected beads. Each of these beads can exert a force to the left or right, but each bead only knows the position of its immediate neighbors. There is no knowledge of the overall state of the organism or of beads further away.

"The crucial question now is: Is there a control system, a set of simple rules, a behavioral strategy that each bead can follow individually so that a collective swimming motion emerges—without any central control unit?" says Hartl.

On the computer, the individual beads—the simulated parts of the virtual microorganism—were equipped with a very simple form of artificial intelligence, a tiny neural network with only 20 to 50 parameters, explains Hartl. "The term neural network is perhaps somewhat misleading in this context; of course, a single-celled organism has no neurons.

"But such simple control systems can be implemented within a cell, for example, by means of very simple physical-chemical circuits that cause a specific area of the microorganism to perform a specific movement."

This simple decentralized control system has now been adapted to the computer in search of the most efficient "control code" possible that produces the best swimming behavior. With each version of this control system, the virtual microorganism was allowed to swim in a simulated viscous fluid.

"We were able to show that this extremely simple approach is sufficient to produce highly robust swimming behavior," says Hartl. "Although our system has no central control and each segment of the virtual microorganism behaves according to very simple rules, the overall result is complex behavior that is sufficient for efficient locomotion."

Biology and technology

This result is not only interesting because it explains the complex behavior of very simple biological systems, it could also be interesting for artificially produced nanobots. "This means that it would also be possible to create artificial structures that could perform complex tasks with very simple programming," says Andreas Zöttl (University of Vienna).

"It would be conceivable, for example, to build nanobots that actively search for oil pollution in water and help to remove it. Or even medical nanobots that move autonomously to specific locations in the body to release a drug in a targeted manner."

More information: Benedikt Hartl et al, Neuroevolution of decentralized decision-making in N-bead swimmers leads to scalable and robust collective locomotion, *Communications Physics* (2025). DOI: 10.1038/s42005-025-02101-5

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