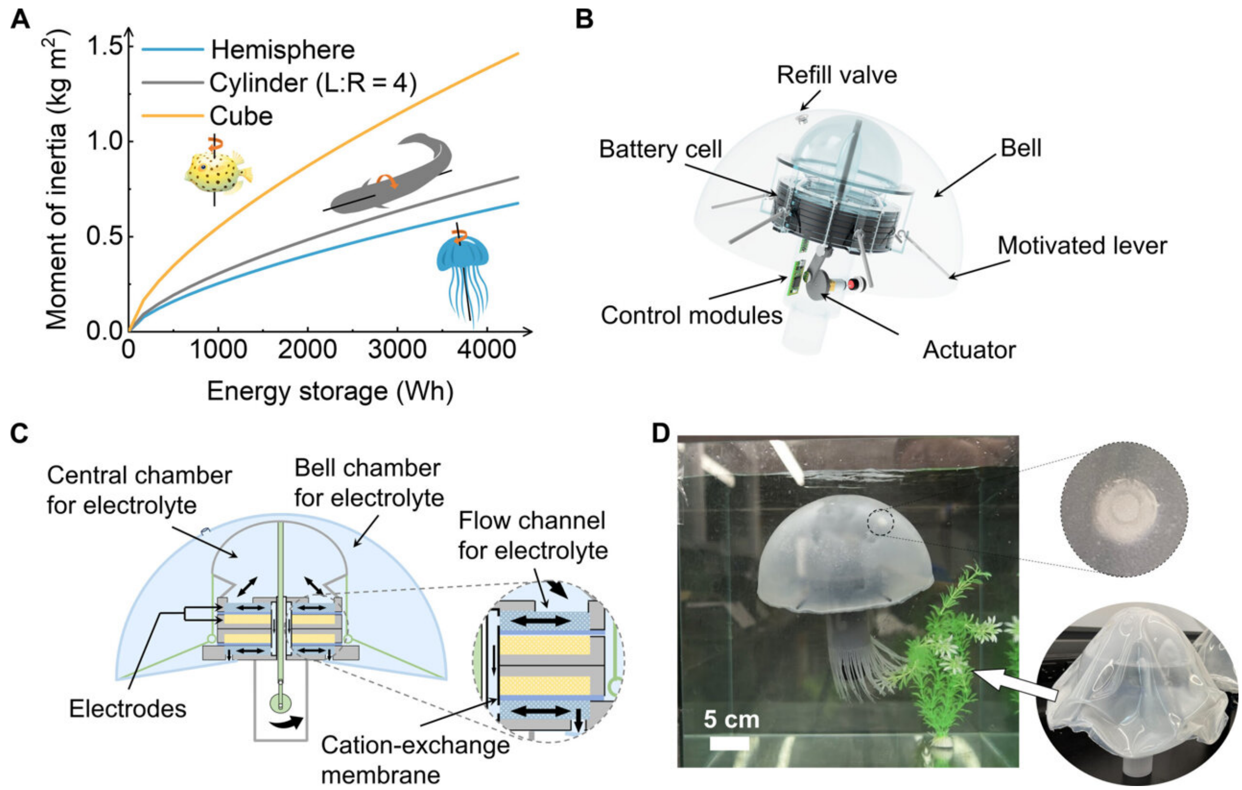
'Embodied energy' powers modular worm and jellyfish robots

January 27 2025, by David Nutt



A jellyfish robot powered by the RFBs. Credit: *Science Advances* (2024). DOI: 10.1126/sciadv.adq7430

In the same way that terrestrial life evolved from ocean swimmers to land walkers, soft robots are progressing, too, thanks to recent Cornell research in battery development and design.

A modular worm robot built by the Organic Robotics Lab and a jellyfish that was a collaboration with the Archer Group, both in Cornell Engineering, demonstrate the benefits of "embodied energy"—an approach that incorporates power sources into the body of a machine, to reduce its weight and cost.

The worm and jellyfish are direct descendants of an aqueous soft robot, inspired by a lionfish and unveiled in 2019, that could store energy and power its applications via a circulating hydraulic fluid—i.e., "robot blood." Similar blood sustains the new species, but with an improved design for greater battery capacity and power density.

"The jellyfish has much more capacity for its weight, so the duration it can travel is even longer than the fish," said Rob Shepherd, professor of mechanical and aerospace engineering, who led both projects. "The worm is the first version we've done above ground. When it's underwater, you get buoyantly supported, so you don't need a skeleton. It doesn't need to be rigid.

"This is how life on land evolved," he said. "You start with the fish, then you get a simple organism and it's supported by the ground. The worm is the simple organism, but it has more degrees of freedom."

The beating heart, and the pumping blood, of both robots is what's called a redox flow battery (RFB), in which electrolytic fluids dissolve and release energy through a chemical reduction and oxidation, or redox, reaction.

For the jellyfish-shaped robot, the two research groups built an RFB with a tendon that, when pulled, changes the shape of the bell and propels the creature upward. When the bell relaxes, it sinks back down. The real innovation, according to Shepherd, is the battery improvements made by the team led by Lynden Archer, the James A. Friend Family

Distinguished Professor of Engineering and dean of Cornell Engineering.

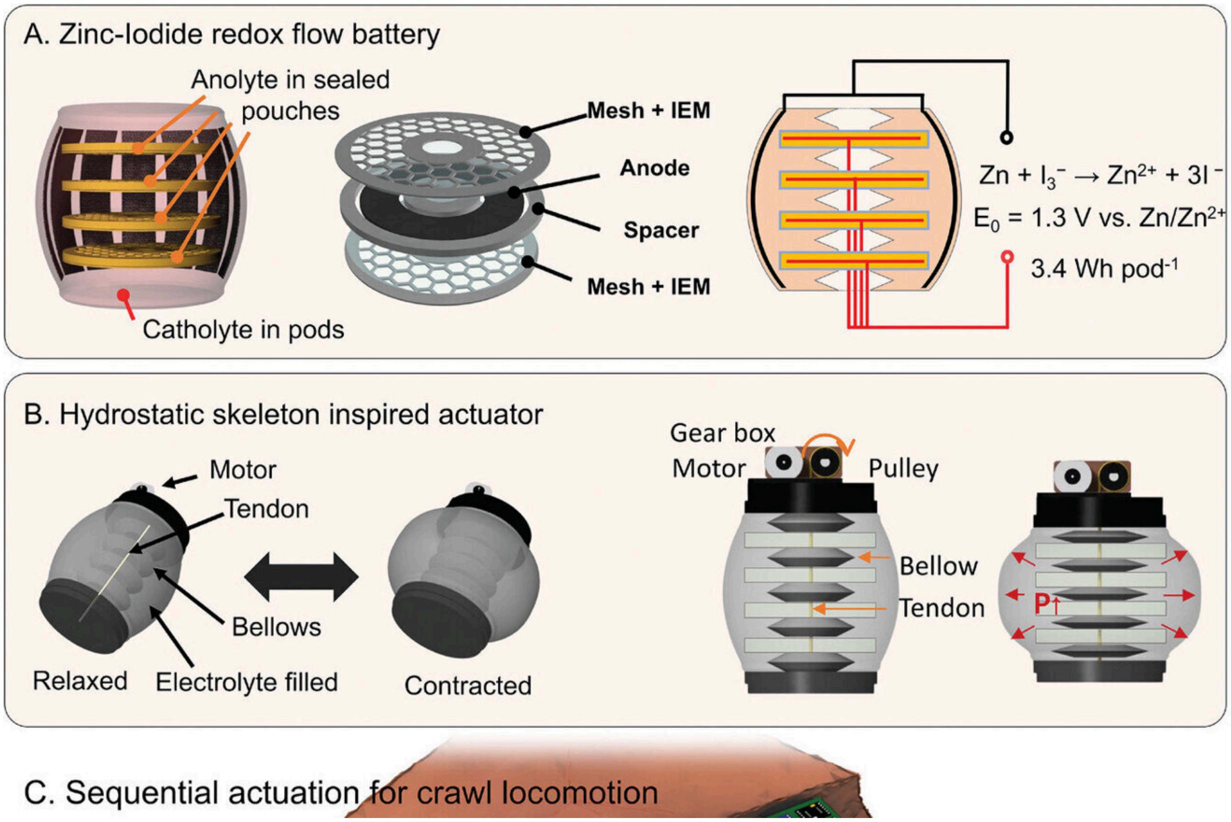
The robot features a pair of redox batteries: zinc iodide (ZnI_2) and zinc bromide ($ZnBr_2$). In order to circumvent the buildup of dendrites on the batteries' electrical substrates, which can stymie charging and discharging, the researchers applied graphene to better match the crystal planes and allow more even plating of the zinc.

In the ZnBr battery, bromine was added to the iodine to enhance ion transport. Those changes increased the battery capacity and power density, making for a faster and more agile jellyfish robot with an operational lifetime of about 90 minutes.

The key innovation of the worm robot was its compartmentalized design. The worm's body is a series of interconnected pods, each containing a motor and tendon actuator so the worm can compress and expand its shape, as well as a stack of anolyte pouches immersed in catholyte.

A crucial part of the design was the decision by postdoctoral researcher Chong-Chan Kim, the study's lead author, to use a dry-adhesion method to automatically bond Nafion separators to the worm's silicone-urethane body as it was printed. The separator keeps the anolytes and catholytes apart while allowing a charge to move between them, which then drives electrons through the motor.

"There are a lot of robots that are powered hydraulically, and we're the first to use hydraulic fluid as the battery, which reduces the overall weight of the robot, because the battery serves two purposes, providing the energy for the system and providing the force to get it to move," Shepherd said. "So then you can have things like a worm, where it's almost all energy, so it can travel for long distances."



Modular pod for self-contained actuation in soft robots. Credit: *Advanced Materials* (2025). DOI: 10.1002/adma.202414872

The researchers tested two modes of movement. The worm can inch along the ground, with each pod contracting and then pushing itself forward; the worm can also push its way up and down a vertical pipe like a caterpillar, a technique known as two-anchor crawling.

The robot is not exactly speedy—it would take 35 hours to travel 105 meters in a single charging—but it is faster than other hydraulically powered worm bots. As for potential applications, the worm is particularly well suited for exploring long and narrow passageways, such as pipes, and possibly conducting repairs.

Likewise, the jellyfish robot would be an ideal low-cost tool for ocean exploration because it can be carried along with the current, then swim up to the surface to send and receive communications, before sinking back down.

In the future, Shepherd anticipates making high-capacity, embodied-energy robots with the same type of lithium-polymer batteries, but that also have skeletons and can walk.

The result will be something that is more "like us," he said. "An imperfect organism. But still doing pretty good."

Anunth Ramaswami '25 co-authored the worm robot study published in *Advanced Materials*..

The lead author of the jellyfish study, published Nov. 27 in *Science Advances*, was Xu Liu, Ph.D. '24. Co-authors included Archer; Yong L. Joo, the BP Amoco/H. Laurance Fuller Professor in the Smith School of Chemical and Biomolecular Engineering (Cornell Engineering); Shuo Jin, Ph.D. '20; doctoral student Yiqi Shao; Autumn Pratt, Ph.D. '21; Duhan Zhang, Ph.D. '18; Kiki Lo '22; and Amir Gat and Sofia Kuperman with Technion-Israel Institute of Technology.

More information: Chong-Chan Kim et al, Soft, Modular Power for Composing Robots with Embodied Energy, *Advanced Materials* (2025). DOI: 10.1002/adma.202414872

Xu Liu et al, The multifunctional use of an aqueous battery for a high capacity jellyfish robot, *Science Advances* (2024). DOI: 10.1126/sciadv.adq7430