BIOMIMETICS

Squid-inspired robots perform swimmingly

Nicole W. Xu

A squid-like robot leverages resonance to match the swimming efficiency of biological animals.

Although the ocean comprises over 70% of Earth's surface area and is responsible for crucial processes such as climate regulation, the ocean has remained a source of mystery, with less than 20% explored to date. Traditional approaches for ocean monitoring include unpiloted underwater vehicles (UUVs), such as autonomous underwater vehicles and remotely operated vehicles (ROVs). These tools have been used to successfully uncover new animal behaviors and map the ocean floor. However, many UUVs are still limited by high power consumption and cannot operate in particular areas of the ocean, such as small crevices where the vehicles might incur damage, or in areas where high noise signatures could disrupt more sensitive marine life (*1*, *2*).

Bioinspired underwater vehicles could represent an alternative to UUVs and present new opportunities in ocean exploration and monitoring (*3*). Animal models provide a sensible solution to the challenges of developing marine robotics, which include high power consumption, maneuverability, damage tolerance, task performance, and adaptability to unknown, unstructured environments (*4*), because animals are well adapted to selective pressure. However, each model organism provides specific advantages and disadvantages for robotic design. Among swimming animals, fish and manta rays can travel over long distances with swift speeds and agility (*3*). Aquatic invertebrates, such as jellyfish and cephalopods, offer new insights because of their simplicity and ability to exploit resonance for enhanced efficiency. In particular, the fastest aquatic invertebrates are squids, with swimming speeds up to 8 m s^{-1} using pulse-jet propulsion (*5*).

Writing in *Science Robotics*, Bujard *et al.* (*6*) demonstrate a squid-inspired soft robot that leverages resonance to enhance its swimming performance. Their soft robot achieves an energy efficiency that matches its biological counterparts. Resonance is defined as a physical property of a system, in which a vibration of large amplitude occurs when the system is driven at a frequency at or near its natural frequency. In comparison, smaller amplitudes occur when driven at other frequencies. This concept of mechanical resonance has been described in hydromedusan jellyfish, modeled as an oscillating system. Hydromedusae tend to swim at or near the resonant frequency of the bell, which produces 40% increases in the amplitude of oscillation with substantial reductions to the energetic cost (*7*).

Existing swimming robots that mimic fish, rays, and jellyfish using entirely mechanical components have been demonstrated in laboratory experiments. Although some of these biomimetic robots can outperform their natural counterparts, most bioinspired robots still have speeds and efficiencies orders of magnitude less than biological organisms. This is, in part, because of a lack of resonance exploitation in robotic design. However, Bujard and colleagues (*6*) use a linear oscillator model for resonant swimming to design a squid-like robot.

With a natural frequency of 10 Hz, this flexible robot exhibits energy-efficient metrics, including high propulsive efficiencies and low costs of transport (COTs; defined as the ratio of power to speed, scaled by mass and gravitational force), with a peak speed of 26 cm s^{-1} when driven slightly below the natural frequency at 9 Hz. These COT values

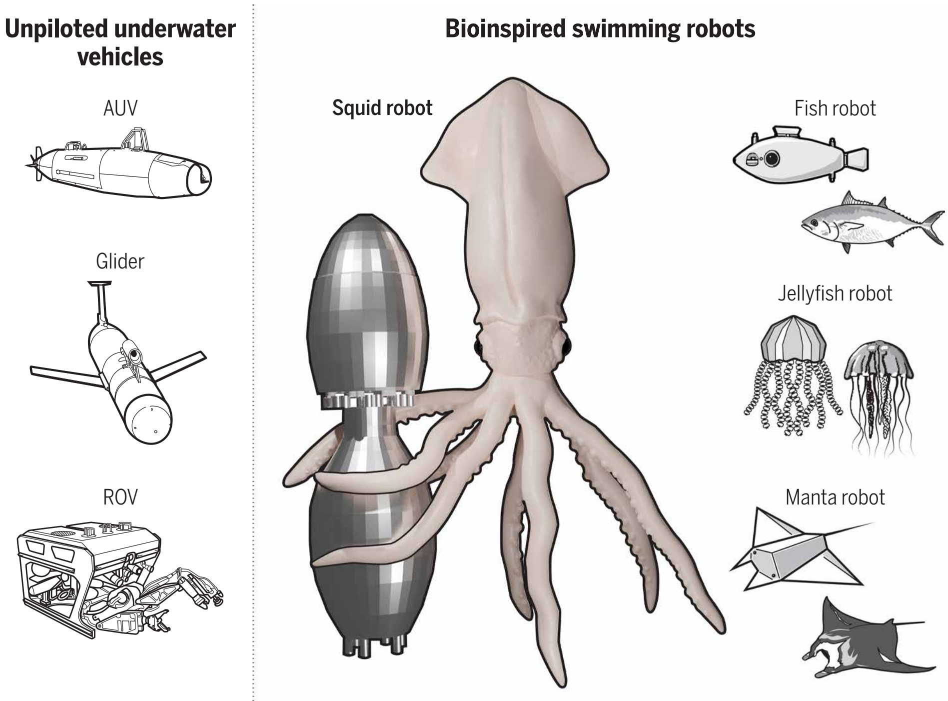

Fig. 1. A menagerie of bioinspired robots for ocean monitoring. The ocean contains a multitude of complex and largely underexplored environments. A diverse set of tools and technologies are needed to study it. Examples of traditional UUVs include autonomous underwater vehicles (AUVs), such as gliders, and remotely operated vehicles (ROVs). In addition to these unpiloted underwater vehicles (far left), bioinspired underwater vehicles can use the best of both natural and artificial design. Examples of such vehicles and their biological counterparts include robotic fish, jellyfish, manta rays, and squids, including the squid-inspired robot by Bujard *et al.* (*6*).

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Graduate Aerospace Laboratories (GALCIT), California Institute of Technology, Pasadena, CA, USA.
Email: nicolexu@alumni.stanford.edu

are comparable to the upper range of *Aurelia aurita*, a species of moon jellyfish known for the lowest reported COT compared to all other animals. This underscores the utility of leveraging resonance in soft robots, with an approach that has already been demonstrated naturally by animals that use elastic energy storage to enhance their propulsion.

Bujard and colleagues (*6*) also propose that resonance enables power to scale linearly with speed, instead of cubically as posited in fluid dynamics. Their hypothesis could potentially address the relationship between COT and swimming speed in other robotic systems, such as biohybrid robotic jellyfish. Jellyfish robotically driven at higher swimming frequencies have demonstrated a threefold increase in speed at only a twofold increase in COT (*8*); the mechanism and the relationship between power and swimming speed remain open questions, possibly elucidated by evaluating resonant effects.

In addition to advances in flexible robotics, these squid-inspired robots offer a new potential technology for ocean exploration. To date, underwater vehicles inspired by fish (*9*) and jellyfish (*10*) have successfully been deployed in ocean environments. In particular, the Soft Robotic Fish (SoFi) has navigated through coral reef environments alongside aquatic animals. This is a strong proof of concept that swimming robots can be used to remotely explore marine life using bioinspired methods of propulsion that reduce disturbances to the environment (*9*). In comparison, the squid-inspired robot in (*6*) has comparable speeds to SoFi, at a quarter of the mass, which suggests that further advances toward building smaller and more efficient vehicles are imminently possible. However, the squid-inspired robot is currently limited by an external tether to a power source and has smaller stroke ratios than natural squids because of material property constraints. Future advances in long-lasting or self-replenishing batteries, flexible materials, vehicle maneuverability, and wireless underwater communication will aid in this endeavor.

Moving forward, there is an ocean of opportunity in designing bioinspired swimming robots. With so little of the ocean definitively studied, both traditional and biologically inspired UUVs can be used to expand existing knowledge of the natural world. Such applications include further deep-sea expeditions using ROVs to observe marine ecosystems, SCUBA surveys to support conservation, and a menagerie of bioinspired vehicles that can potentially approach or interact with aquatic life (Fig. 1).

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