COLLECTIVE BEHAVIOR

A 3D underwater robotic collective called Blueswarm

Artur Wolek[1]* and Derek A. Paley[2]

A swarm of agile fish-robots uses vision-based implicit coordination to demonstrate self-organizing behaviors in a laboratory tank.

Engineers look toward nature for principles of sensing, locomotion, and coordination that will one day enable robots to gracefully navigate underwater landscapes and use collective behaviors, much like a school of fish. Bioinspired autonomous underwater vehicles (AUVs) arguably have many advantages over their propeller-driven counterparts. For example, fish-like locomotion can improve efficiency and maneuverability. Robotic fish are also stealthier by virtue of their appearance, quiet propulsion, and inconspicuous wake signatures. Their small size and low cost enable them to be deployed in great numbers. Although they may not carry large powerful sensors, a distributed network of mobile sensors may offer superior coverage in cluttered areas that are challenging for traditional AUVs (e.g., coral reefs, ports, and shallow coastal waters). Applications for such ocean sensing networks may include environmental monitoring, infrastructure inspection, surveillance, and subsea search.

Although progress has been made toward implementing individual fish robots, schools of robotic fish have yet to be developed. Existing underwater multi-robot systems often use explicit communication and localization methods to coordinate, for example, by exchanging GPS-tagged messages over radio (on the surface) or using sophisticated acoustic modems and inertial navigation systems (while underway). However, these methods require expensive and bulky instrumentation and are therefore not suitable for the dynamic 3D coordination envisioned for robotic fish schools. Instead, techniques that use simple sensors and local interaction rules to achieve global behaviors are preferred. Writing in *Science Robotics*, Berlinger *et al.* move closer to this goal through the development of an underwater collective that achieves complex 3D behaviors using only local implicit vision-based coordination (*1*).

The team designed a swarm of 3D-printed miniature (13 cm long) robotic fish called Bluebots (see Fig. 1). These bioinspired AUVs have independently controlled fins that are oscillated by an electromagnetic actuator to enable agile maneuvers, such as turning or stopping in place and quickly diving and ascending. Inspired by the bioluminescence and prominent stripes exhibited by some fish species, Bluebots have blue-light LEDs embedded

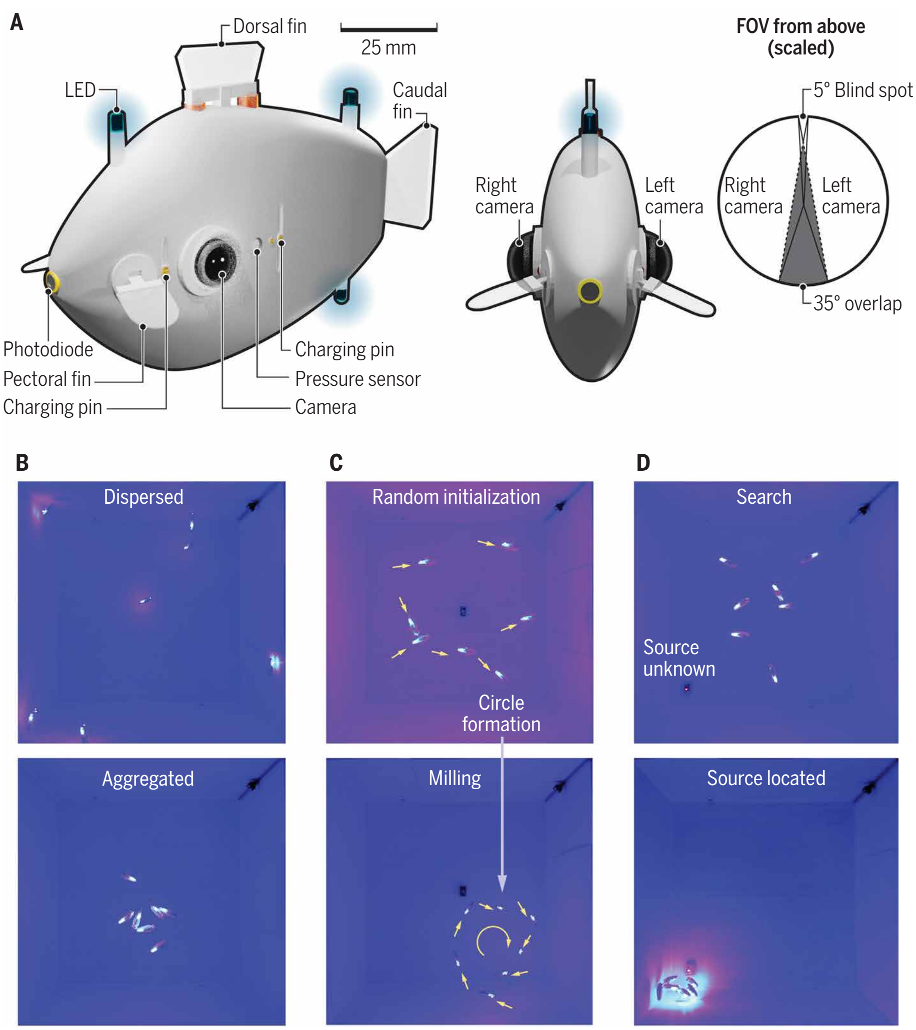

Fig. 1. Bluebot design and photographs of the Blueswarm platform in action. (**A**) Key components of a Bluebot include four oscillating fins that enable agile maneuvers and two omnidirectional cameras that detect the blue-light LEDs of neighbors. The Blueswarm demonstrated several collective behaviors using implicit vision-based coordination, including time synchronization of LED flashes (not shown), (**B**) controlled dispersion, (**C**) dynamic circle formation, and (**D**) a search operation for a red LED light source composed from multiple behaviors.

CREDIT: A. KITTERMAN/*SCIENCE ROBOTICS*; PHOTOS IN (B) AND (C) FROM FIGURES 3 TO 5 IN (1).

[1]Department of Mechanical Engineering and Engineering Science, University of North Carolina at Charlotte, Charlotte, NC 28223, USA. [2]Department of Aerospace Engineering and the Institute for Systems Research, University of Maryland, College Park, MD 20742, USA.
*Corresponding author. Email: awolek@uncc.edu

on their exterior and pairs of cameras (in place of eyes) to detect them. Every half-second, a machine-vision algorithm determines how many Bluebots are visible and infers their relative distances and angular positions. Using only these visual observations and a simple set of interaction rules, the Bluebots—collectively referred to as a Blueswarm—have demonstrated a range of self-organizing behaviors.

For example, the team demonstrated time synchronization, wherein the Bluebots were deployed in the tank with initially randomly flashing LEDs that gradually flashed in unison, like some species of fireflies. To achieve this synchronization, each Bluebot responds to a perceived flash of a neighbor by advancing the start time of their next flash according to the Mirollo-Strogatz model (*2*). This type of synchronization can be useful for synchronizing drifting clocks underwater where there is no access to a reference time.

The group then illustrated the Bluebots' ability to control their spatial density by moving according to a virtual force model (*3*). Bluebots experience artificial forces from all of the neighbors they detect—attractive forces to maintain cohesion and repulsive forces to avoid collisions. Tuning the strength of the forces enables controlled dispersion to expand or contract the volume covered by the swarm. The Blueswarm is also capable of formation behavior using a simple strategy of rotating clockwise or counterclockwise (depending on the presence or absence of another robot in the camera's view) to drive the robots into equally spaced positions around a circle.

The researchers further showed how collective behaviors can be sequenced to form more sophisticated ones. For example, Bluebots located an unknown red-light source by having individuals transition between search, alert, and gather behaviors. The Bluebots swarmed around the tank until one or more of them detected the source, and then they triggered additional Bluebots to move toward the source and gather nearby.

The coordination approach used by Berlinger and colleagues demonstrates the advantages of decentralized implicit communication that is common in biological systems. In their experiments, the robotic fish are not perfect—they use low-cost actuators and sensors and occasionally make mistakes, such as bumping into each other or confusing water surface reflections for other Bluebots. Although there is no central plan in place, the robots achieve their objective by relying on decentralization and implicit coordination. Their dynamic behaviors are robust to failures of agents or sensor faults.

A key limitation of the work by Berlinger and colleagues is that their Blueswarm experiments were conducted in a controlled laboratory setting. The successful deployment of a large-scale network of fish robots in the ocean will require several challenges to be surmounted. Robust sensing of neighboring fish is perhaps most important among these. The vision-based sensing methods used by Berlinger *et al.* would be problematic in the field where visibility is reduced due to ambient light, vegetation, obstacles, and water turbidity. However, augmenting vision-based systems with other sensing modalities, such as with flow sensing based on artificial lateral lines (*4*) or electroception (*5*), could improve reliability. Furthermore, without the confines of tank boundaries, flow disturbances, obstacles, and the sheer scale of the ocean will present additional challenges. Behaviors and navigation strategies are needed that prevent individuals from becoming disoriented and separated from their collective. Last, advances in energy-storage technologies and the design of more efficient locomotion using soft flexible bodies will play an important role in improving the limited endurance of existing designs.

REFERENCES

1. F. Berlinger, M. Gauci, R. Nagpal, Implicit coordination for 3D underwater collective behaviors in a fish-inspired robot swarm. *Sci. Robot.* **6**, eabd8668 (2020).
2. R. E. Mirollo, S. H. Strogatz, Synchronization of pulse-coupled biological oscillators. *SIAM J. Applied Math.* **50**, 1645–1662 (1990).
3. J. E. Lennard, I. Jones, On the determination of molecular fields. *Proc. R. Soc. London* **106**, 441–477 (1924).
4. L. DeVries, F. D. Lago, H. Lei, X. Tan, D. A. Paley, Distributed flow estimation and closed-loop control of an underwater vehicle with a multi-modal artificial lateral line. *Bioinspir. Biomim.* **10**, 025002 (2015).
5. M. A. MacIver, E. Fontaine, J. W. Burdick, Designing future underwater vehicles: Principles and mechanisms of the weakly electric fish. *IEEE J. Oceanic Eng.* **29**, 651–659 (2004).

10.1126/scirobotics.abf4315

Citation: A. Wolek, D. A. Paley, A 3D underwater robotic collective called Blueswarm. *Sci Robot.* **6**, eabf4315 (2021).

Science Robotics

A 3D underwater robotic collective called Blueswarm

Artur Wolek and Derek A. Paley

Sci. Robotics **6**, eabf4315.
DOI: 10.1126/scirobotics.abf4315