ANIMAL ROBOTS

Robots and animals teaming up in the wild to tackle ecosystem challenges

Thomas Schmickl[1] and Donato Romano[2,3]*

Copyright © 2024 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works

Interactively teaming up animals and robots could facilitate basic scientific research and address environmental and ecological crises.

In an era of unprecedented environmental challenges (*1*), the paradigm of biologically effective robotics emerges as a promising approach to address ecological predicaments (*2*). These challenges necessitate innovative methodologies that transcend traditional boundaries and merge biological insights with mechatronic technologies by bridging the conceptual chasm between natural and digital realms. Robotic agents reproduce the morphological and functional attributes of biological organisms, emulating or even synergistically merging their sensory and actuation capabilities.

The emerging field of animal-robot interaction systems is characterized by biomimetic, bioinspired, or at least biocompatible robots that engage in behavioral or ecological interactions with living animals. It provides multiple innovative opportunities by harnessing engineering and robotic techniques to carry out complex biological experiments and by yielding novel biohybrid systems for laboratory conditions and for wild habitats. Such systems offer innovative applications in overcoming several severe challenges, which we discuss in this Focus.

The emerging field of biohybrid robotics has been characterized by three seminal studies: First, the Leurre project in 2007 (*3*) developed autonomous robots to infiltrate cockroach aggregations during their collective decision-making on shelter choices in laboratory experiments. Second, the Virtual Fences project socially integrated robotic neck collars into cattle herds in 2008 (*4*). Third, the cyborg insect field started with a seminal "neuro-cybernetics" study in 2009 (*5*). In the following 15 years, a plethora of studies have integrated robots with various animal species (Fig. 1). Recently, an autonomous robotic system was shown to be capable of bridging two ecologically distant animal species (honey bees and zebrafish) by allowing coordinated decision-making (*6*). Another multispecies approach was shown to protect native animal species (frog tadpoles) from invasive species (mosquitofish) by using predator-like robotic deterrents (*7*). Today's biohybrid robots augment entire social insect societies, supporting their growth and survival and ultimately aiming for beneficial ecosystem-level effects (pollination services) in the wild (*8*). In addition, robots can foster social learning to improve ecological awareness in real animals (*9*).

Animal-robot interaction systems follow one of three concepts: robots that modulate animal behaviors (Fig. 1, A to C), robots that are affected by animal behaviors (Fig. 1, G to I), and lastly, robots that fully integrate into animal societies by closing the sensor-actuator loop (Fig. 1, D to F). These approaches face different challenges, they focus on diverse goals, and they yield potential for various applications.

One class of robotic systems focuses on the effects that the robot can impose on animals by reinforcing, altering, modulating, or even suppressing behaviors. Such systems are often highly biomimetic because animals are very tough referees when it comes to biomimicry. They will show the desired behavioral responses to the behaviors and stimuli produced by the robot only if they accept the robot as a relevant living entity (e.g., a conspecific). Therefore, it is crucial to identify the appropriate interaction channels, which can be visual (Fig. 1, A and B, D and E, and G and H), vibrational or acoustic (Fig. 1, C and H), olfactory or chemical (Fig. 1E), thermal (Fig. 1F), electrochemical (Fig. 1G), or mechanical or haptic (Fig. 1, B and C and G). The signals in those channels must resemble their natural templates to avoid triggering unnatural behavioral artifacts. This is epistemologically important to generate valid biological knowledge (*10*) and to satisfy ethical requirements to minimize animal stress. Such animal-robotic systems enable innovative biological experimentation for a deeper understanding of organismic communities and ecosystems (Fig. 1, B and C and E) or allow contingency technologies against invasive species and spreading pests (Fig. 1, A and D). These robots are mainly aiming to elicit very specific behaviors (e.g., mating or courtship) or to spatially aggregate, repel, steer, or control the animals.

Another class of robotic systems react mostly to behaviors shown by animals. Such systems are often mere observers that should remain as invisible as possible to the animals; thus, there is no major requirement for biomimetic shapes and forms. They need to be equipped with technology that allows them to detect the animals because they are mostly aimed at tasks such as monitoring, observing, or tracking animals. They need to be operational over extended periods in harsh and large habitats, necessitating designs that prioritize flexibility, robustness, and resilience. Such systems observe animals over the long term, either under semi-wild conditions (Fig. 1I) or fully in the wild (Fig. 1, F to H). They either collect behavioral data or perform ecological monitoring tasks. In wild and uncontrolled environments, where human-made materials can have adverse ecological impacts, the development of more sustainable robots is essential. Such designs can involve using biodegradable materials or even incorporating living organisms as components of robotic systems (Fig. 1G).

The most complex setting for animal-interacting robots is full closed-loop integration: For a deep integration into animal societies, communities, and ecosystems, such systems fully close the behavioral

[1]Artificial Life Laboratory, Department of Zoology, Institute of Biology, University of Graz, Leechgasse 42, A-8010 Graz, Austria. [2]BioRobotics Institute, Sant'Anna School of Advanced Studies, Viale Rinaldo Piaggio 34, Pontedera, 56025 Pisa, Italy. [3]Department of Excellence in Robotics and AI, Sant'Anna School of Advanced Studies, 56127 Pisa, Italy.
*Corresponding author. Email: donato.romano@santannapisa.it

Downloaded from https://www.science.org at Scuola Superiore Sant Anna on November 25, 2024

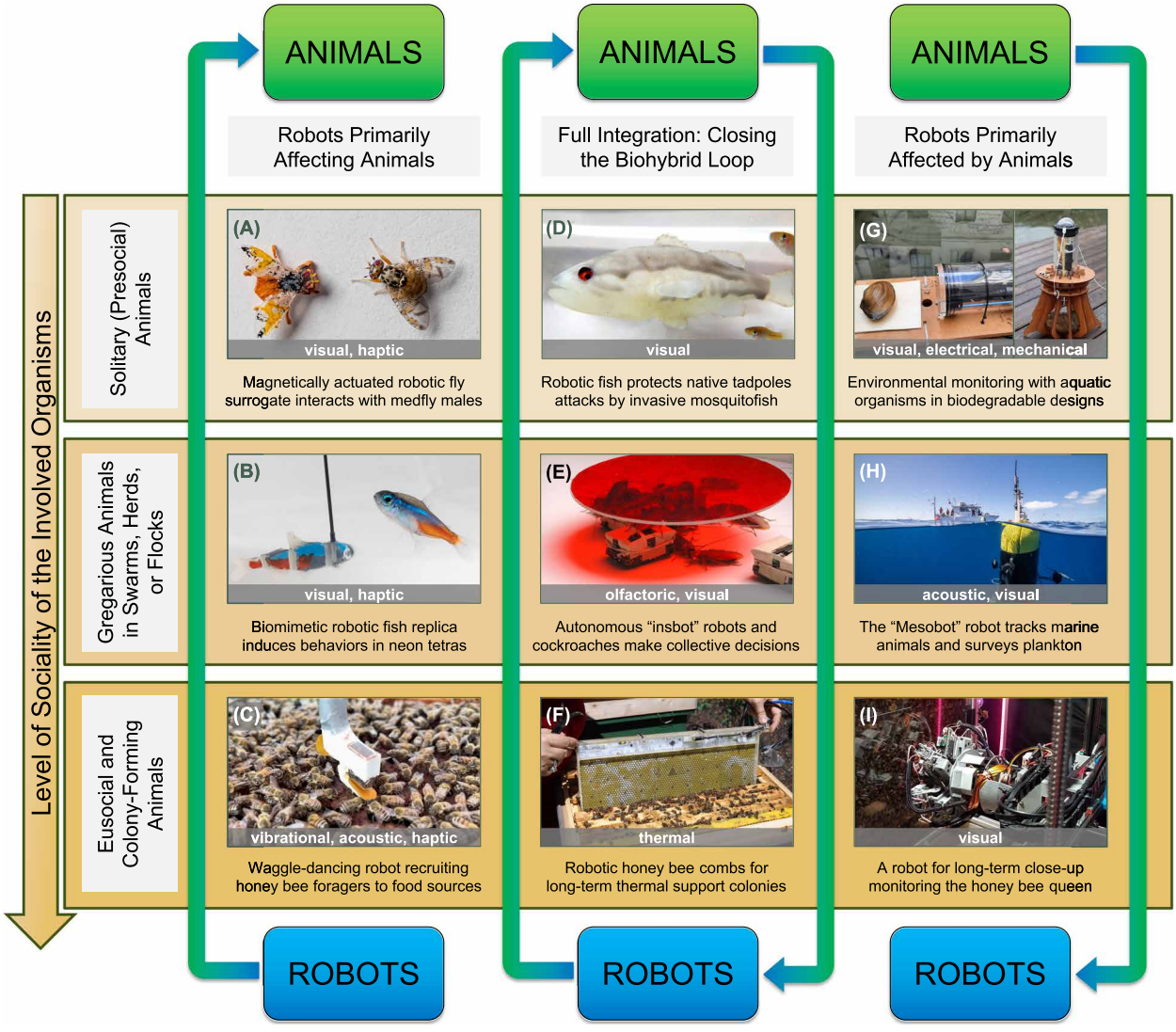

Fig. 1. Overview of the implementation of animal-robotic systems based on species of diverse levels of sociality. Left: Systems with information/effect primarily flowing from robots to animals. (**A**) Medfly approaching a robotic fly surrogate. (**B**) (i) Robotic fish for interaction with neon fish. (**C**) Waggle-dancing robot interacting with honey bees. Middle: Systems establishing a closed feedback loop between animals and robots. (**D**) Robot protecting native frog tadpoles from an invasive fish species. (**E**) Autonomous "insbots" cooperate with cockroaches in collective decision making. (**F**) Robotic honey bee combs for closed-loop thermal support of overwintering clusters and brood. Right: Systems with information/effect primarily flowing from animals to robots. (**G**) Long-term environmental monitoring with living animals as sensors and biodegradable robot materials. (**H**) Tracking of aquatic animals and surveying plankton in the ocean by Mesobot. (**I**) Robotic system for long-term close-up observation of honey bees.

feedback loop between the animal and the machine. This allows researchers not only to study these societies from within (Fig. 1, B and C and E and F) but also to control them (in other words, shepherd) without physically constraining or stressing them. Often, a subtle modulation of some animals' behaviors can be sufficient to alter the behavior of the overall group (*3*, *4*). Other fields of application are environmental management and protection (Fig. 1D) or medical test procedures, for example, using robots to prepare better standardized animals for drug testing (*11*). The crucial challenges are to understand relevant social interactions, collective information processing, and macroscopic emergent dynamics that arise from the sum of all microscopic agent-to-agent interactions. When seeking suitable "hooks" to integrate robots into animal systems, social interaction mechanisms are most promising because of their natural inclination toward interaction. Such social interactions are frequently present in species with low or medium levels of sociality, for example, gregarious animals or animals living in swarms, flocks, or herds (Fig. 1, B, E, and H). Unique opportunities are offered by eusocial insect colonies, for example, ants, wasps, honey bees, and termites (Fig. 1, C, F, and I). These species not only offer a plethora of complex and omnipresent social interaction mechanisms but also act in fundamental roles as important keystone species within their ecosystems. Even a low number of interactions can produce a strong ultimate effect because social interaction patterns tend to cascade and spread within animal communities. However, a hidden danger looms: Behavioral artifacts can cascade

PHOTO CREDITS: ((A) AND (B)) SCUOLA SUPERIORE SANT'ANNA, PISA; (C) EU-FET PROJECT HIVEOPOLIS, COURTESY OF T. LANDGRAF (FU BERLIN); (D) COURTESY OF G. POLVERINO (UNIV. TUSCIA) AND M. PORFIRI (NYU); (E) COURTESY OF J.-L. DENEUBOURG (ULB, BRUSSELS), F. MONDADA (EPFL, LAUSANNE), AND J. HALLOY (UNIV. PARIS CITÉ); (F) EU-FET PROJECT HIVEOPOLIS, EPFL, LAUSANNE, GROUPE MOBOTS, UNIV. GRAZ, ARTIFICIAL LIFE LABORATORY; (G) EU-FET PROJECT ROBOCOENOSIS, UNIV. GRAZ, ARTIFICIAL LIFE LABORATORY; (H) MARINE IMAGING TECHNOLOGIES LLC/COPYRIGHT WOODS HOLE OCEANOGRAPHIC INSTITUTION

Downloaded from https://www.science.org at Scuola Superiore Sant Anna on November 25, 2024

within animal societies. Thus, a fundamental understanding of the animal and its environment is crucial to generate social biohybrids. Fortunately, animal-interacting robots are the right tool to generate those necessary insights.

As the rapid emergence of more and more organism-interacting robots shows, the integration of robotic agents into organismic communities provides a paradigm shift in environmental conservation, offering innovative strategies for biodiversity preservation, sustainable agriculture, and aquaculture management. This deep integration will firmly anchor robotics research in science, enabling novel platforms for scientific discovery. As robotics becomes increasingly embedded into the wild, these systems will also be vital allies in fostering symbiotic relationships, enhancing ecological resilience, and shaping ecosystems.

REFERENCES

1. R. H. Cowie, P. Bouchet, B. Fontaine, The sixth mass extinction: Fact, fiction or speculation? *Biol. Rev.* **97**, 640–663 (2022).
2. D. Romano, E. Donati, G. Benelli, C. Stefanini, A review on animal–robot interaction: From bio-hybrid organisms to mixed societies. *Biol. Cybernetics* **113**, 201–225 (2019).
3. J. Halloy, G. Sempo, G. Caprari, C. Rivault, M. Asadpour, F. Tâche, I. Saïd, V. Durier, S. Canonge, J. Ame, C. Detrain, N. Correll, A. Martinoli, F. Mondada, R. Siegwart, J.-L. Deneubourg, Social integration of robots into groups of cockroaches to control self-organized choices. *Science* **318**, 1155–1158 (2007).
4. N. Correll, M. Schwager, D. Rus, Social control of herd animals by integration of artificially controlled congeners, in *From Animals to Animats 10: Proceedings of the 10th International Conference on Simulation of Adaptive Behavior (SAB, 2008)* (Springer, 2008), pp. 437–446.
5. A. Bozkurt, R. F. Gilmour, A. Sinha, D. Stern, A. Lal, Insect–machine interface based neurocybernetics. *IEEE Trans. Biomed. Eng.* **56**, 1727–1733 (2009).
6. F. Bonnet, R. Mills, S. Schönwetter-Fuchs, M. Szopek, J. Halloy, S. Bogdan, L. Correia, F. Mondada, T. Schmickl, Robots mediating interactions between animals for interspecies collective behaviors. *Sci. Robot.* **4**, eaau7897 (2019).
7. G. Polverino, V. R. Soman, M. Karakaya, C. Gasparini, J. P. Evans, M. Porfiri, Ecology of fear in highly invasive fish revealed by robots. *iScience* **25**, 103529 (2022).
8. R. Barmak, M. Stefanec, D. N. Hofstadler, L. Piotet, S. Schönwetter-Fuchs-Schistek, F. Mondada, T. Schmickl, R. Mills, A robotic honeycomb for interaction with a honeybee colony. *Sci. Robot.* **8**, eadd7385 (2023).
9. D. Romano, C. Stefanini, Robot-locust social information transfer occurs in predator avoidance contexts. *Int. J. Soc. Robot.* **16**, 489–500 (2024).
10. E. Datteri, The creation of phenomena in interactive biorobotics. *Biol. Cybern.* **115**, 629–642 (2021).
11. H. Ishii, Q. Shi, S. Fumino, S. Konno, S. Kinoshita, S. Okabayashi, N. Iida, H. Kimura, Y. Tahara, S. Shibata, A. Takanishi, A novel method to develop an animal model of depression using a small mobile robot. *Adv. Robot.* **27**, 61–69 (2013).

10.1126/scirobotics.ado5566

Downloaded from https://www.science.org at Scuola Superiore Sant Anna on November 25, 2024