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EDITORIAL

Animal–robot interaction—an emerging field at the intersection of biology and robotics

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Abstract

The field of animal–robot and organism–robot interaction systems (ARIS, ORIS) is a currently rapidly emerging field in biorobotics. In this special issue we aim for providing a comprehensive overview of the cutting-edge advancements and pioneering breakthroughs within this scientific and engineering discipline. Therefore, we collected scientific articles that delineate and expound upon the complexity of these remarkable biohybrid systems. These configurations stand as engineered conduits, facilitating the accurate investigation and profound exploration of the multifaceted interactions between robotic devices and biological entities, including various fish species, honeybees and plants. Also the human factor plays a role in this collection, as we also include a philosophical perspective on such systems as well as an augmented reality setup that brings humans into the loop with living fish. Within our editorial purview, we categorize the scientific contributions based on their focal points, differentiating between examinations of singular agent-to-agent interactions, extensions to the social stratum, and further expansions to the intricate levels of swarm dynamics, colonies, populations, and ecosystems. Considering potential applications, we delve into the multifaceted domains wherein these biohybrid systems might be applied. This discourse culminates in a tentative glimpse into the future trajectories these technologies might traverse, elucidating their promising prospects for both scientific advancement and societal enrichment. In sum, this special issue aims at facilitating the convergence of diverse insights, at encapsulating the richness of the ARIS and ORIS domain, and at charting a course toward the untapped prospects lying at the nexus of biology and robotics.

1. Introduction

Within the realm of scientific exploration, an emerging field is focusing its efforts towards an ambitious aspiration: the establishment of animal–robot and organism–robot interaction systems (ARIS and ORIS hereafter) [1]. This ambitious pursuit revolves around the seamless fusion of living organisms and nonliving elements, ingeniously crafting pioneering configurations of biohybrid systems. In this innovative domain, scientists and engineers explore the frontiers of biology, robotics, and synthetic materials to create remarkable amalgams that blur the boundaries between the organic and the artificial. The ultimate aim is to breathe life into bio-artificial entities, giving rise to biohybrid populations and/or communities that possess both biological and robotic agents.

Some recent examples of ARIS include robotic agents interacting with bees [2], flies [3], fish [4]. Robotic agents have also been used to interact with other organisms such as plants [5, 6] and microorganisms [7]. The seamless integration of technical artifacts into organismic societies presents a tough challenge, necessitating their harmonious blending and interaction within the group, akin to supplementary nodes within natural social and ecological interaction networks. This integration must be executed with utmost precision to ensure the proper development of biohybrid systems. This quest for biohybrid systems is founded on the belief that combining the ingenuity of living systems with the precision and versatility of technological elements will usher in an era characterized by the emergence of groundbreaking advancements for society and for the environment. This will likely open up prospects for designing resilient, adaptive, and multifunctional systems, poised to revolutionize a wide array of industries such as medicine, energy, and environmental sustainability. As this novel field of science continues to evolve, it may not only challenge our understanding of life itself, but it may also spark ethical considerations by prompting in-depth discussions about the boundaries of human intervention in the natural world. Nevertheless, the allure of this endeavor lies in the potential to unlock new possibilities for enhancing human existence and to reshape the very fabric of life as we know it.

The resulting structure of ORIS and ARIS is a biohybrid system, which can be studied at various system levels, thus they are intrinsically multi-level biohybrid systems. These could be individual actions (in biology also sometimes called 'proximate mechanisms') at the microscopic level, which affect the overall system's behavior and actions at the macroscopic level. This is usually also the level at which the system as a whole is most often studied and benchmarked. In multi-organism systems, such as eusocial, social and gregarious species, there often exist also several mesoscopic levels within the system, which emerge from dynamics of interaction within specific groups of agents. Interactions happen most frequently within a system layer and there is an upwards causation and often also a downwards feedback in the system, allowing for many feedback loops in the system. If those feedbacks 'jump' across certain system layers, the systems might be prone to exhibit pattern formation and other emergent properties [8], which can become challenges for designing such systems, but also potential game-changer properties to unlock novel beneficial features like swarm intelligence and strong resilience. Except for special cases, like broadcast-type communication (e.g. pheromone spreading), causation usually goes upwards layer-by-layer in nature. However, the artificial agents within ARIS and ORIS might also generate upward causation in the system by altering the environment globally for the whole population of agents, based on individually encountered cues or interactions, what is another potential 'game changer' property of ARIS and ORIS from a system science perspective.

2. Aim of the special issue and the collected articles

This special issue intends to explore and showcase the latest research, developments, and insights related to the interaction between robots and animals/organisms. This interdisciplinary field combines elements of robotics, animal behavior, ethology, AI, and human–computer interaction. Herein, we host a collection of highly relevant papers on the topics of ARIS and ORIS. These studies approach such topics at various system levels by associating biomimetic and bioinspired technological agents (robots and similar devices) with single living organisms, with social groups of organisms, or even with whole populations and ecosystems. These approaches are either theory-driven by establishing and validating models of such systems, or empirically driven (empirical studies on hardware and organisms). In the following we shortly describe and summarize those articles' findings and implications.

In this editorial, the collected articles are classified into three distinct sections (e.g. microscopic, mesoscopic and macroscopic view), each focusing on a specific level of interaction between robots and animals/organisms. Our editorial also contains a section on ethical and philosophical considerations including a contribution that examines the philosophical analysis of how robotics within the ARIS and ORIS frameworks contribute to advancing knowledge. By organizing the collected articles into these sections, the editorial aims to provide a structured overview of the diverse research landscape at different scales. This way, we offer readers a comprehensive exploration of the interaction between robots and animals/organisms across various system levels and disciplines.

3. Microscopic view

On the microscopic level, where interactions usually involve a single robot and a single living organism, ARIS and ORIS can exhibit several interesting properties. These interactions are more focused and life-like, often revealing specific behavioral and physiological responses from the individual animal/organism and the robot. Understanding the microscopic properties of animal-robot interactions is essential to inform the design and development of robots that can successfully interact with individual animals. It also helps to unveil mechanisms governing animal responses to natural or artificial stimuli, contributing to the broader understanding of animal intelligence, behavior, and ecology.

The study by Romano and Stefanini [9] explores the mechanisms promoting mixed-species fish aggregations, using the neon tetra (*Paracheirodon innesi* Myers) as model organism. In their experiments, robotic fish replicas with different colors and morphologies were used to test the affiliation behavior of fish individuals. The fish showed decreasing preference in shoaling with biomimetic, blue, red, and grey replicas. Blue color's greater visibility underwater could explain this observation. Red color, possibly indicating nonoptimal behavioral status, also influenced the fishes' shoaling behavior. The presence of biomimetic predators extended shoaling duration, while the presence of food reduced it, confirming the role of antipredator and competition in affecting heterogeneous shoals.

Abdai *et al* [10] tested individual dogs' and cats' perceptions of animate vs. inanimate objects using an artificial unidentified moving object (UMO). The authors observed that dogs approach and interact with the UMO more than cats. In these experiments, both species displayed distinct behavior towards animated UMOs, but dogs also performed increased looking behavior. Dogs' greater curiosity might be due to cats' heightened stress in novel environments.

In the experiments described in the article by Maxeiner *et al* [11], authors used a robotic fish replica (programmed as a socially competent leader) to interact with individual female guppies (*Poecilia reticulata* Peters) and to investigate how they adapt their rules based on social contexts. The guppies followed the socially competent robot longer when it adapted to their avoidance movements. Socially competent robots outperformed non-responsive and randomly changing robots, displaying attractive behavioral variability, better leadership performance, requiring fewer approach attempts, and eliciting longer following behavior.

Bierbach *et al* [12] used a biomimetic robot to investigate anticipation in guppies. A significant portion of the individuals tested reached the robot's destination earlier than the robot in the final trial, indicating the presence of global anticipation. For local anticipation, fish adapted their turning behavior in response to the robot, indicating anticipation of the robot's movements. This study suggests that guppies can anticipate predictably behaving social partners concerning movement locations and dynamics. This ability may have evolved as a mechanism to adapt to various social interaction partners, considering fish's consistent behavioral differences.

An ORIS focusing on plants has been proposed by Buss *et al* [13]. The authors investigated phytosensing in living plants through the utilization of electrical potential and tissue impedance measurements, to infer information about the surrounding environment, and to be implemented in the future for urban air pollution monitoring. Organisms of the species *Zamioculcas zamiifolia* (Engler) and *Solanum lycopersicum L.* were exposed to diverse stimuli while their electrical signals were measured. Multiple statistical discriminant analysis and deep learning methods were evaluated for stimulus classification. This blackbox approach proved feasible, offering valuable insights for selecting appropriate classifiers.

4. Mesoscopic view

On the mesoscopic level, encompassing interactions within specific groups of both robotic and natural agents, ARIS and ORIS unveil an additional dimension of complexity: social group behavior. These interactions, taking place among clusters or cohorts of entities, illuminate collective behaviors, social dynamics, and coordinated activities. This mesoscopic perspective on the system offers insights into how robotic agents can seamlessly integrate into and influence natural groups, forging hybrid ensembles that harmonize individual goals with collective objectives. These insights have implications for fields ranging from animal behavior studies to multi-agent system design, influencing how robots partake in group behaviors and adapt to dynamic social structures.

The article by Cazenille *et al* [14] uses computational methods to analyze and to predict the emergent properties of a mixed swarm. This swarm consists of gregarious insects socialized together with autonomous biomimetic robots, which interact on the microscopic (individual, proximate) level. The authors developed a method to automatically produce microscopic models through evolutionary computation procedures. These models are then adjusted to best predict macroscopic data representing bifurcation diagrams of emergent shelter choices. This method translates across all system layers, most prominently it predicts the groups sizes in the shelters, thus we attribute it to the mesoscopic system layer perspective.

The article by Kernbach [15] describes autonomous underwater robots that physically mimic the electro-communication of weakly electric fish. The study demonstrates that these biomimetic robots can infer typical mesoscopic properties like group sizes or distances to groups of agents and group synchronization of pulsing. In this exemple, the robots act as study surrogates for the real electric fish, thus it does not directly implement or study an ARIS or ORIS, but presents a robotic surrogate for these natural counterparts, an important stepstone that can help to implement such systems in a meaningful way in future.

A unique ARIS is described by Hu *et al* [16] which brings a group of fish together into a closed-loop interaction with human actors via a technological interface, so that both, fish and humans, perceive an enhanced VR-augmented environmental experience. The results of these experiments indicate that such artificially enhanced closed loop interactions have an effect on the general mood and on the exhibited behaviors on both sides.

5. Macroscopic view

At the macroscopic level, which spans colonies, populations, and ecosystems, ARIS and ORIS hold the potential to revolutionize our comprehension of intricate ecological systems. By interfacing robotic agents with entire communities of organisms, these interactions unveil emergent patterns, population dynamics, and ecosystem-level effects. Such a deepened understanding of biological and ecological systems can reshape conservation strategies, can shed light on environmental responses, and may even offer a novel lens into the interplay between technology and biodiversity. As ARIS and ORIS extend their reach to these expansive scales, they offer a unique perspective on the interdependence of organisms and machines, charting a course towards holistic ecological insights and fostering a symbiotic relationship between science, technology, and nature.

Typical examples for biohybrid systems that show strong emergent properties on the macroscopic system level are swarms or groups of robots integrated into larger populations of animals, e.g. robots interacting with social or eusocial animals. In this special issue, the work by Lazic and Schmickl [17] investigates how a group of waggle-dance imitating biomimetic robots could alter the hive-mind of collective foraging decisions of a honeybee colony and analysis. Using an extended version of a conglomerate of several state-of-the-art honeybee nectar foraging models [18–22] the authors investigate if such robots can lead a colony to revert a previously made collective foraging decision and how many robots it would take to operate in a beehive. The predicted emergent foraging decisions are then analyzed from multiple perspectives: what are the benefits and gains for the honeybee colony, for a farmer and beekeeper and for the vegetation through the pollination service provided by the bees?

In another work included in this special issue, Rajewicz *et al* [23] proposed a biohybrid system, merging mechatronics with living organisms, to enable continuous, long-term aquatic data collection. The authors describe the development of biohybrid entities that are endowed with autonomous power from microbial fuel cells, and that integrate living organisms like zebra mussels and water fleas. These biohybrid entities mayoffer a groundbreaking method for extensive, continuous aquatic monitoring, forming the foundation for an early-warning system.

6. Ethical and philosophical considerations

This special issue also features a contribution focusing on a philosophical analysis of the role that robotics, in the framework of ARIS and ORIS, can play in the advancement of knowledge. In particular, Tamborini and Datteri [24] examined whether or not biorobotics qualifies as science and what the role of technoscience is/can be within it. The distinction between proximal and distal biorobotic hypotheses is used to differentiate between technoscientific and scientific biorobotic studies. The authors argue that biroboticians can be both scientists and technoscientists, with technoscientists playing a crucial role in understanding and shaping the bio-hybrid and technological world of the 21st century. By studying robotic systems and animal-robot interactions, biorobotics contributes to our understanding of the increasingly interconnected biological and technological aspects of our world.

Overall, in the examples we discuss here, all interactions with the natural organisms occurred in a minimally-invasive way by presenting external stimuli to the organisms. However, even external stimuli can become stressful for an animal. We think that the application of ARIS, and thus also the research required to establish such systems, requires ethical guidelines that guide these works from an animal-rights perspective. In our opinion, research with ARIS and ORIS asks for guidelines that can easily be followed with animal–robotic interaction systems, where the boundaries of the legal requirements are sometimes set quite wide. For example, insects are legally not specifically protected in most countries. Still, in our opinion, it will be beneficial for the wellbeing of these animals, and also for the wellbeing of the minds of the experimenters, to follow a specific set of principles that aim at minimizing the stress load and potential risks for the animals to a minimum. Currently, the individual labs that act in the field are called to set their specific shortlist of rules and constraints, tailored to their specific species and stimulation types. Ultimately, the development of a feasible and relevant set of such rules should be approached by the community in a collective and constructive way.

7. Potential fields of application of ARIS and ORIS

The profound impact of ARIS and ORIS triggers a paradigm shift in our interaction with the natural world. These frameworks intertwine the research tracks of various fields, such as technology, biology, and human insight, transforming how we engage with animals and ecosystems. Scientifically, ARIS and

ORIS offer unique perspectives into animal behavior, cognition, and social dynamics, enhancing disciplines from ethology to neuroscience. Conservation biology may profit from better computational models with increased predictive power as ARIS and ORIS reveal species' responses to environmental changes, aiding targeted interventions for biodiversity preservation. Beyond science, ARIS and ORIS bridge artificial and biological realms, fostering empathy and understanding. Immersive interactions offer profound insights into animal cognition and behavior, nurturing respect for life's intricacies.

Firstly, such systems can allow researchers to integrate artificial agents deeply into organismic societies, communities and ecosystems, allowing them to study such systems from within. For example these artificial agents can induce noise or out-of-equilibrium actions onto the system, allowing to benchmark the resilience of the overall systems by the reactions that are triggered by these disturbances [25, 26]. Secondly, artificial agents that engage in interaction with natural organisms can establish standardized behavioral interaction protocols, benefiting human society through potential utility in the pharmaceutical industry. Robots often interact with zebrafish (*Danio rerio* Hamilton) which are a standard model animal in molecular biology and pharmaceutical labs [27, 28]. Also lab mice and other rodents interact with robots, some of them rather biomimetic [29], others not so [30]. Thirdly, ARIS and ORIS enable novel minimum-stress methods in agriculture and livestock management [17, 31]. Finally, such agents open the door to novel ecological monitoring and ecosystem-management strategies [32, 33], if the agents interact with organisms in the wild, in agro-ecosystems or in other dedicated structures (e.g. greenhouses, mass-rearings in biofactories, etc) [34].

8. Conclusions

This special issue serves as a collaborative platform, bringing together articles on ARIS and ORIS to foster interdisciplinary cooperation among researchers. Its overarching goal is to disseminate knowledge and contribute to the sustainable integration of robots in diverse animal and ecological contexts. Beyond conventional science, ARIS and ORIS converge technology, biology, and humanity, paving the way for a harmonious coexistence with nature. This endeavor illuminates a future where enlightened interconnectedness guides our interactions with the environment.

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