Toward Population-Level Biohybrid Systems: Bioinspiration and Behavior

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Abstract
For biohybrid systems involving robot interactions with a large and varied population of animals, it could be beneficial to deploy a morphologically and behaviorally varied population of robots into the environment, for successful interactions across the full diversity of the relevant biological population. In this paper, we briefly summarize our work in two areas integral to this effort: (1) computational investigations of bioinspired methods for retaining population-level variance under evolution; and (2) quantitative evolutionary analysis of genetics and morphology. We also consider ideas for Cognitive Science-inspired work in designing goal-directed behaviors for the robots in biohybrid systems. Based on the underlying idea that robot designs with deeper roots in biology can result in more effective biohybrid systems, our perspectives and approaches could illuminate new commonalities between evolved robot populations and evolved biological populations, which would ideally improve the robots as tools for scientific insight into animals, their behaviors, and their environments.

Introduction
By integrating robots into a population of animals and having them interact with those animals in natural environments, robots can improve our ability to understand animal behavior, our ability to collect information about it, and our ability to influence it (Bonnet et al. 2019; Karakaya et al. 2020). For this to be most successful — e.g., for highly effective influence on animal behavior or data collection about behavior in natural environments — the robots must be accepted by and integrated into the animal population; reflecting the importance of the biological context, bioinspired methods for robot design seem apt for bio-compatible results.

To maximize robot compatibility with a diverse population of animals, and to maximize congruity with methods and insights from biological sciences, our perspective is founded on having a diverse population of robots in a biohybrid system; by virtue of its diversity, the robot population could have greater environmental compatibility and more natural interactions with the diverse population of animals. Such a population-centered approach to bioinspired robots for animal interaction may not yet be well studied, so, in this paper, we treat it as a challenge problem to be embraced: How can we create a diverse population of robots to blend in and interact with a diverse population of animals in natural environments?

Population-Level Modeling
We introduce our approach here by modeling simple terrestrial animals that locomote by flexing articulated segments (Fig. 1B-C). Ultimately, our work is motivated by applications to biohybrid systems with fish, a diverse group of animals commonly targeted in biorobotics, robo-ethology, and biohybrid systems (Roberts et al. 2014; Romano et al. 2017; Kim et al. 2018). We are creating robots capable of integrating with predator-prey behaviors of a population of fish, and here we consider elements needed for a diverse, bioinspired robot population: genomic diversity, morphological diversity, and “cogni-mimetic” modeling and behavior. Below, we briefly summarize some of our work in bioinspired evolutionary methods for genomic and morphological diversity, along with ideas for Cognitive Science-inspired behavior models for robot populations.

Genomic Diversity
Because of their simpler genetics, asexual organisms are our starting point. While mutation is the primary generator of random change in the genome of an asexually reproducing individual, other factors may also be in play when diversity of the population is considered (Blows & Hoffman, 2005). The genetic variance of an asexual population is a function of multiple factors (Ronsheim & Bever, 2000), including life-history trade-offs, distribution distance of offspring, mutation rate in the germline, and genome size. Asexual populations under directional selection tend to lose additive genetic variance, as only a subset of the population reproduces every
generation; thus, as demonstrated in our work (Fig. 1), populations with higher median fitness tend to have reduced genetic variance. Without genetic variance among individuals, the population ceases to respond to selection, adaptation stalls, and we can misinterpret the stagnation as a local optimum, an adaptive peak. Thus, we need to understand the genetics of a population in order to understand — and control — its evolutionary dynamics, including the origin of morphological diversity. As we make genomes and genetic processes more bioinspired, we anticipate that the coevolution of animal and robotic populations will improve, with similar types of cognitive and behavioral responses and natural interactions.

Morphological Diversity
In addition to genetic factors and selection, morphological diversity in a population is shaped by development. Random errors in the transcription of the genome increase morphological variance in the absence of mutation and in combination with it as we have shown in our self-propelled terrestrial robots (Fig. 2). While developmental factors have been shown to impact the evolution of robots (Bongard, 2013; Brawer et al. 2017), the interaction between mutation and transcriptional errors has not previously been studied. Given that the expression of the genome is the first step in understanding evolutionary dynamics and evolvability (Wagner, 2013), this causal mechanism deserves more attention. In particular, since transcription error is a mechanism separate from mutation, it can be used independently to manipulate morphological variance in populations. Thus, mutation and transcription error can serve as separate control variables to use in experiments co-evolving the animal and robotic populations in a biohybrid system. Keeping in mind that animal populations are continuously evolving, any biohybrid system in the wild will need its robotic population to continually co-evolve if the system is to operate robustly.

Cognition and Behavior
Formalism of cognitive models in biohybrid societies is a substantial challenge, as is formalism of biohybrid societies in general (see Hamann et al. 2016). To focus efforts to meet that challenge, we identify predator-prey behavior as a useful case to study; Predator-prey interactions include multiple individuals with clear goals; it is essential to animals such as fish, and modeling it can encompass elements that are essential for studies of intelligent behavior, such as learning and robustness across potentially unpredictable environments. In our perspective, we recognize that fish are intelligent, goal-directed complete agents (Pfeifer et al. 2005), and we propose that methods drawn from Cognitive Science should be employed to design or derive the models of intelligent behavior to implement in our robot population. Consistent with bioinspired or bio-mimetic approaches that could underlie the morphology of a robot population — which would ideally lead to broad, natural acceptance of the robots by animals in natural environments — we suggest that a cogni-mimetic modeling approach would be desirable, inspired by Cognitive Science insights into continuously reactive, intelligent goal-directed behavior and reflecting similar conceptual structures in cognitive models. Approaches such as BDI (Bratman, 1987), Semantic Pointer Architecture (Eliasmith, 2013), H4W-DAC (Verschure et al. 2014), DI-HDCA (Aaron, 2016), Dynamical Field Theory (Schöner, 2016), and could potentially apply. Ideally, a modeling framework would readily enable the representation of high-level cognitive concepts that guide behavior, to complete the connection from evolutionary mechanisms to morphology to biomechanics to high-level cognition. Identifying or creating a framework that supports conceptual integration across those levels is central to creating a bio/cog-inspired robotic model of the full range of phenomena desired for a robot population that can integrate and interact with animals in natural environments.

Conclusion
The simple terrestrial animals modeled here are a starting point for modeling fish. The perspective proposed in this paper can be viewed as cohesively connecting one bioinspired collection of elements, and then extending that collection into another one. On one level, it connects evolutionary computation to all aspects of a complete cognitive agent, from genomes to biomechanical levels of development and morphology to mental and cognitive levels of high-level action selection and goal-directed behavior. Then, beyond that — and heeding the reminder that the fundamental unit of evolution in biology is a population (Hartl, 2020), a perspective not always aligned with individual-based approaches in evolutionary robotics — it further extends the broad scope of complete cognitive agents by integrating it with biology and evolutionary science, stretching from population-level evolution and variance, into and through the scope of complete agents, and then into population-level behaviors, with the attendant possibilities of emergence. Overall, this kind of integrative bioinspired modeling, with its foundations in science and reach into computational methods, has the potential to deeply establish and extend biohybrid animal-robot systems as tools for population-level study of, and impact on, behavior in natural environments.

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References


