Robot Behavior

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Introduction

Behavior is typically defined as the activity of an organism, machine, or natural phenomenon, particularly in response to external stimuli. This definition is broad, and applies to robots and animals alike. A categorical difference between animals and robots is that the latter are typically designed by human beings to perform a set of highly constrained objectives, while animal behavior is typically rich and largely unconstrained.

The overwhelming majority of all robots manufactured worldwide are industrial robot manipulators. These are typically open kinematic chains – that is, a series of links and joints, whose first joint is mounted to a stationary base – with an end effector mounted to the final link. It is true that many industrial robot arms are at least approximately anthropomorphic, with six degrees of freedom: a waist joint, shoulder joint, elbow joint, and three degree-of-freedom wrist. However, the connection to biology ends there because the mechanical design, construction, control, and performance is unnatural: industrial robots are rigid, extremely precise, and some designs can produce forces on the order of tens of kilonewtons (thousands of pounds) while maintaining positioning error on the order of centimeters. In fact, some industrial manipulators can accelerate automobile engines at several times the acceleration due to gravity. These machines can produce a wide array of movements reliably, repeatably, and for much longer than animals can without fatigue. By many metrics, these machines already outperform animals, so a natural question arises: Why copy nature?

Once programmed, industrial manipulators are generally quite limited in their ability to respond to their environment and typically execute an even more limited repertoire of behaviors. These machines are rigid not only mechanically, but behaviorally as well. Animals, on the other hand, exhibit complex and nuanced responses to sensory stimuli, can perform a wide range of behaviors, and seem to deal with uncertainty and complexity more effectively than current robotic designs. This has motivated some research groups to study the principles of animal behavior to design robotic systems on the basis of these principles.

In this article, we turn our attention to biologically inspired robots: those that are designed to emulate or copy some set of morphological and/or behavioral characteristics from nature. In this context, what are the relations between robotic and animal behavior and how can they be a source of insights for both engineers and biologists? Engineers increasingly look to the animal world for inspiration, but, as described later, translating animal behavior into robotic systems is fraught with pitfalls. Nevertheless, with care, this approach has led to technological advances, several examples of which are reviewed here. Robotic behavior can also be used by biologists to test specific hypotheses. This opens up the door for productive synergies between engineers and biologists, seeking to advance the state of the art in both fields.

Briefly, robots can be divided into three categories. Type 1 robots are not directly inspired by, nor designed to share features with biological systems. Robots that operate in assembly lines or household robots such as the Roomba™ (iRobot Corporation) fall into this category. Type 2 robots are those that are biological inspired, incorporating specific behavior features observed in animals in order to achieve some set of functional objectives. Robots such as those envisioned by the popular science fiction writer Isaac Asimov fall into the Type 2 category. Type 3 robots are those that are built to test specific hypotheses about animal systems. These robots can be particularly helpful when certain manipulations of the actual animal are not possible. Here, we focus on Type 2 and Type 3 robots.

Type 2: Biologically Inspired Robot Behaviors to Service Human Needs

Even relatively simple animals can perform far more complex and nuanced behavior than can the most advanced robots. Take, for example, the case of winged flight. Fixed-wing aircraft can outperform animals in terms of velocity and lift, but cannot match flapping animal fliers in terms of maneuverability. In recent years, engineers have produced many biologically inspired flapping fliers, called *ornithopters*, in an effort to match the maneuverability of nature's designs. These Type 2 robots take their inspiration from the natural world to achieve a limited set of functional objections. Several of these machines are reviewed in the examples given later, but first some of the challenges in the process of bioinspiration are described.

Challenges in Translating Biological Behavior into Robotic Inspiration

The basic hypothesis underlying many efforts in bioinspiration is that animal behavior systems have been optimized over time by evolutionary processes. The notion is that organisms, through millions of years of evolution, have come up with fundamental design properties that solve problems associated with the natural constraints defined by the physical properties of the universe. The result is that animals can be high performing with respect to a variety of engineering metrics. Determining those fundamental design features for use in robotic design, however, is more difficult than simply copying specific features of an organism.

Take, for example, the differences among independently evolved vertebrate fliers such as pterosaurs, birds, and bats. Obviously, a pterosaur and bird and a bat do not look identical; in fact they are quite different in terms of the details of their design. If these animals were indeed 'optimal,' one might expect a greater convergence of materials, morphologies, and physiological properties between species. So, how does a roboticist determine those features of animal design that will contribute to better robots? As a start, the roboticist needs to consider that every behavior an animal performs must be interpreted in the context of the entirety of the organism. This is due to three features of animal behavior.

First, behavior is mediated by mechanisms that are shared by other behaviors and physiological functions of the animals. Therefore, the mechanisms for any particular behavior cannot be assumed to be optimal for that behavior. In fact, a better assumption is that the mechanisms for any particular behavior are actually suboptimal. For example, songbirds produce songs that are necessary for successful reproduction. Nevertheless, the mechanisms for song production use organ systems that are shared for grooming, breathing, eating, and thermoregulation. Ergo, birds are not optimized for producing song alone.

Second, the behavior of an animal occurs in the context of its evolution. The evolutionary history of an organism imposes a set of constraints on behavior and physiological mechanisms that may not be easily described or understood. A trivial example of this sort of phylogenetic constraint might be food manipulation in birds and mammals. Birds must use the hindlimbs to manipulate food items because the forelimbs have been co-opted for flight, whereas most mammals use the forelimbs. In other words, evolution makes use of the features that are available, rather than developing an optimal solution 'from scratch.'

Third, behavior must be interpreted in terms of the ultimate evolutionary goal of the animal, which is reproduction. Thus, although the proximate goal of a particular behavior might appear straightforward, such as prey capture, that behavior represents only part of the behavioral repertoire necessary for reproduction. In short, no animal is optimized to achieve any single behavior, but rather they are designed to carry out a suite of behaviors that are sufficient for survival and reproduction.

Design features can more reliably be determined via a comparative approach. Specifically, comparisons among species permit the identification and separation of those features that are unique to a particular organism or a clade of organisms, versus those features that are similar among organisms or clades. Of interest are those features that are similar among the widest array of animals: those features are most likely to represent the fundamental design constraints for a particular category of behaviors.

Evolutionarily speaking, such similarities can arise from two sources. Similarities across clades can be plesiomorphic – meaning that the feature arose in an evolutionary event that occurred long ago and that all the extant clades have inherited that feature. Indeed, there are genetic sequences that are found in very distantly related species, and can be shown, using quantitative analysis, to have first occurred well over 200 million years before present. Similarities can also be homoplastic – meaning that the feature arose independently in different clades. This process is also known as 'convergent evolution.' A simple example of convergence is the eyes of vertebrates, cephalopods, and cnidarians. Each of these clades independently evolved an eye with a single lens in front of a photoreceptive sheet.

Convergent strategies are of particular interest. Take, for example, the case of legged locomotion. Comparative studies that carefully account for dimensional scaling reveal remarkably similar mechanics and energetics across dramatic variations in, morphology (including 2-, 4-, 6-, and 8-legged runners) and body size (millimeters to meters). These similarities include mechanical and metabolic energetics, gait, stride frequency, and ground reaction forces. These ubiquitous scaling relations have been used to inform the design and implementation of biologically inspired legged robots such as the RHex robotic hexapod described below.

Examples of Type 2 Biologically Inspired Robots

There is a rich history of biological inspiration in mechanical systems, perhaps starting with the human fascination with avian flight. Leonardo da Vinci is widely known for his study of birds and he produced many conceptual designs of artificial flying machines, including an early design for a hang glider which was ultimately successful. Many of his designs were for ornithopter flapping flight. While it is true that for centuries, engineers have been inspired by flapping flight, ultimately engineers separated the mechanisms of thrust, lift, and, to some extent, control. This is a decidedly nonbiological approach, because for birds and other flapping fliers, flapping wings perform all three of these tasks.

Deciphering these integrated, shared mechanisms has proven a substantial challenge for engineers and has remained essentially unsolved for decades. In the last two decades, substantial progress has been made in this regard, encouraging researchers to return to the design and construction of ornithopters inspired by animal flapping flight. This has been facilitated by a multitude of technological and scientific advances. For example, improved fabrication technology has accelerated the rate at which new designs can be implemented and tested. Moreover, a wide variety of actuator technologies, such as electroactive polymers (EAPs), are becoming available for use as artificial muscles that offer many of the characteristics of animal muscle. From a scientific standpoint, there have been increasingly sophisticated studies into the mechanisms for lift and maneuvering in natural flapping fliers, including a wide range of new experimental and analysis techniques: high-resolution and high-speed videography, complex 3D fluid simulations, electrophysiological recordings during behavior, etc.

A recent example of the confluence of science and technology is the Micromechanical Flying Insect (MFI; http://robotics.eecs.berkeley.edu/~ronf/mfi.html) project, which began as a collaboration between biologists and engineers at UC Berkeley. These small-scale robotic flying machines are inspired by the discoveries in high-frequency flapping flight of flies. Biological investigations into the mechanisms of unsteady aerodynamics of flies, sensory integration from the haltere, and wing actuation have all fueled MFI technology. Recently, the Harvard Microrobotics Laboratory built a successor to the MFI that generated sufficient lift to take off.

In terrestrial locomotion, basic research at the PolyPEDAL Laboratory at the University of California, Berkeley, has inspired several engineering research labs to build hexapedal robots capable of rapid running and climbing, including the following projects:

- RHex (http://kodlab.seas.upenn.edu/RHex/Home): This is a collaboration between researchers at University of California, Berkeley, the University of Pennsylvania, and McGill University to build a dynamic hexapod capable of high-speed terrestrial locomotion.
- Robots in Scansorial Environments (RiSE; http://www.riserobot.org/): This is a large consortium of researchers from academics and industry, including University of Pennsylvania, University of California, Berkeley, Stanford University, Lewis and Clark College, and Boston Dynamics, Inc., to build biologically inspired climbing machines.

Type 3: Robots as Biological Research Tools

The Role of Robots as Physical Models

Biological hypotheses must often be tested using indirect methods, such as mathematical models and computer simulations. This is particularly true for fields like paleobiology, where direct measurement of behavior is impossible, but it is also true for behavioral biology in general. For example, ethical considerations or technical challenges with small organisms can preclude many types of manipulations and measurements. In this case, computer models and numerical simulations can certainly be helpful, but there are cases when these are not sufficient either. This motivates the use of robotics as a tool for simulating animal behavior in order to test hypotheses.

In a certain sense, physical simulations using a robot are no different than those in a computer. In the context of behavioral biology, however, robot models have two potential advantages over computer simulations. First, computer simulations rely on approximations to the underlying physics of movement that cannot be independently verified. Second, robots are of special importance for investigations of social behavior, because robotic surrogates can be introduced into ecologically relevant settings; these surrogates can then be used to test specific hypotheses about the nature of social interactions in a way that may be impossible using animals alone.

Examples of Type 3 Robots to Model Biological Behavior

The mechanics of flapping flight of the fruit fly is challenging to study for many of the reasons noted earlier. First, the small scale of fruit flies makes instrumentation unfeasible using state-of-the-art technologies. Moreover, accurate mathematical simulations of the aerodynamics are currently an open research problem in the fluid mechanics community, so such simulations cannot, alone, be completely trusted as a test of a biological hypothesis. As a consequence, a team of engineers and biologists developed a Type 3 robot called 'RoboFly,' a large dynamically scaled robotic model of a fly wing, designed to flap in mineral oil. In a hybrid approach, the researchers measured the 3D flight kinematics for real fruit flies turning in free space and replayed the measured wing kinematics (appropriately scaled in time) through RoboFly. RoboFly's large scale facilitated instrumentation of forces and torques, enabling researchers to measure for the first time the forces required during maneuvering. Using the principle of similitude, the forces measured on RobotFly were used to determine the forces at play at the original scale of the fruit fly itself. In a synergistic collaboration, members of the same team have developed a series of Type 2 robots through the MFI project mentioned earlier. These small-scale robotic flying machines are inspired by the discoveries the team has made about flapping flight using RoboFly. This synergy between biologists and engineers – involving the development of both Type 2 (MFI) and Type 3 (RoboFly) robots – is increasingly common.

Another area where biological experimentation can be difficult is in the complex cues used in social communication.

Robot animals can be used introduced into social settings to test the role of specific cues for communication. A recent example this sort of Type 3 robot is 'Faux Frog' that was used to test the role of visual cues in female responses to male calls. Male Túngara frogs produce auditory signals that involve the inflating and the deflating of a large sac. The auditory cues have been known for some time to be effective for attracting mates. However, the movement of the sac itself could be a strong visual cue to females, but disassociating the sac movement and the sounds produced by those movements is not possible in an intact animal preparation. To test the possibility that the movement of the sac was a cue used by females, a robot frog was produced in which the sac movements and sounds could be decoupled. Experiments with this robot showed, for the first time, that the visual cues arising from sac movements had an important role in female perception of frog calls.

In a more complex experiment, Type 3 robot cockroaches imbibed with cockroach chemosensory cues were used to examine the relative contributions of physical and social cues in refuge choice. In an experimental arena, cockroaches will hide under refuges that are provided for them. If two identical refuges are provided, all the cockroaches will nevertheless congregate under a single refuge. A quantitative model for refuge selection was developed, but this model could not be tested using animals because there are no manipulations of the animals that can reliably change the social behavior of the animals. Instead, robot cockroaches that implemented the quantitative model were introduced into the arena with the roaches. The parameters of the model could be changed in the robots, which indeed resulted in changes in the behavior of the cockroaches. These changes showed how social cues contributed to the distributions of cockroaches among the refuges. Interestingly, the behavior of the cockroaches also affected the performance of the robots.

See also: Animal Behavior: The Seventeenth to the Twentieth Centuries; Communication: An Overview; Comparative Animal Behavior – 1920–1973; Darwin and Animal Behavior; Evolution: Fundamentals; Integration of Proximate and Ultimate Causes; Neuroethology: What is it?; Psychology of Animals.

Further Reading

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