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EDITORIAL

Evolving Soft Robots

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Robo

Throughout the history of autonomous robotics (which dates back to the Second World War), much emphasis has been placed on devising algorithms for adaptive control of a machine with a fixed mechanical structure. That is, little effort has gone into shaping the ''body'' of the machine to best complement the controller ''brain'' being developed for it.

There are many reasons for this, one of which can be traced as far back as the 17th century, when René Descartes cleaved humans into corporeal bodies and immaterial souls. Another, more modern—and more mundane—reason is that it is much easier to modify software than hardware. However, researchers in the field of embodied cognition have taught us that intelligence is built upon the fundamental feedback loop between a learner and its environment, which is forged by perception and action: the learner pushes against the world (literally or figuratively) and observes how the world pushes back.

Changes to a robot's control architecture change this feedback loop and thus change what the robot can learn, as well as how well and how rapidly it can learn it. But, of course, changes to a robot's morphology also change this feedback loop, with similar consequences for the acquisition of adaptive behavior. Much more recently, roboticists have developed a healthy respect for the behavioral repercussions of morphology, including work on passive dynamic walkers and a proliferation of exotic aerial drone designs. But still, many of these morphology design decisions are manually devised. In contrast, controllers for robots are now almost exclusively trained using automated methods. This begs the question as to why robot body plans are not also automatically optimized to accelerate the acquisition of adaptive behavior.

Evo Robo

Again, there are many reasons for this ''neurochauvinism.'' One important and obvious reason is, again, that it is difficult to modify bodies compared to brains. Even if the technical challenges are removed, there are considerable challenges in applying optimization to a robot's mechanical construction. Optimization methods that rely on gradient descent do not work well on bodies, because a slight change to, say, the curvature of the underside of a bipedal robot's foot, can greatly impact—or even confound—its ability to walk. Also, bodies do not usually share the properties of artificial neural networks (now more fashionably referred to as deep learners) that make such systems amenable to gradual improvement.

However, these reasons have not seemed to bother Mother Nature much: she has been happily sculpting body plans and nervous systems ever since she ''invented'' the latter about 600 million years ago. Researchers in the field of evolutionary robotics (affectionately known as ''evo robo'') attempt to follow her lead by creating algorithms that mimic the processes of evolution; roboticists who instantiate aspects of specific animals in machinery, in contrast, mimic a *product* of evolution.

Evolutionary roboticists then (the author included) typically broaden an optimization method's reach such that it can gradually improve both the robot's mechanical structure and controller. Besides allowing changes to body and brain, such investigators also usually include other evolutionary details such as maintaining a population of robot variants rather than optimizing a single one, and introducing various methods for trial and error such as mutation and sexual recombination.

The rationale underlying this approach thus runs as follows: if adaptive behavior is learned by pushing against the world and observing how the world pushes back, and different body plans allow robots to push in different ways, some body plans must be ''better'' than others, in the sense that some will allow for more rapid acquisition of useful behavior. We task an evolutionary simulation with automatically finding such body plans.

Such evolutionary simulations are typically more complex and time-consuming than backpropagating error within a neural network controlling a robot. However, there is another challenge with such an approach. Usually, any evolutionary modification to the body plan of a robot that exhibits the rudiments of some desirable behavior usually ''breaks'' that behavior in the offspring: imagine adding a fifth rotor to an already partly functional quadcopter.

This obstacle to enabling evolution to sculpt robot form as well as robot function can be easily traced in the literature. Over 20 years ago, Karl Sims unveiled impressive simulations showing evolved virtual creatures that could run, swim,

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and perform phototaxis. His creatures were typically composed of no more than a dozen parts. Since then, many researchers have attempted to evolve the bodies and brains of autonomous robots, but the resulting robots exhibit no more complexity than Sims's original creatures. Thus, much work in evolutionary robotics is focused on softening the blow of morphological modification, with the hope that this will lead to the evolution of ever more morphologically complex—and thus ever more functionally capable—machines.

Evo Devo Robo

Again, Mother Nature has already beaten us to the punch. One of the most radical changes in our understanding of biological evolution in recent decades has been that genes do not code for traits, but rather that they dictate how traits react to environmental stimuli (or other developing traits). Thus, evolution does not code blueprints of plants or animals, but rather recipes: how an organism changes over the course of its lifetime. This realization led to the creation of a subfield known as the ''evolution of development,'' or ''evo devo'' for short. It follows then that much of an organism's body plan is not hard coded but rather develops in response to the environment. Examples abound: branches and leaves twist to catch the light; muscles grow in response to exercise; scar tissue covers and protects open wounds. Thus, evolutionary changes to morphology are really evolutionary changes to morphological change: that is, how morphology should respond to environmental signals. This may—although this has yet to be proven—introduce gradients into the evolutionary search through morphospace: a limb that grows a little longer and stronger in response to mechanical loading through mutation may still yield a useful limb (''evo devo robo''), compared to an alternative evolutionary system that lacks development (''evo robo'') in which new organisms (or robots) are ''born'' with suddenly longer or stronger limbs that must be controlled by a nervous system previously adapted to control shorter and weaker limbs.

In previous work I have shown that incorporating the evolution of development into robotics can indeed enable evolution to produce useful robots faster, but that work involved traditional robots, modeled as collections of rigid components attached together with a handful of mechanical degrees of freedom.

… Evo Devo Soro?

What would happen if we evolved soft robots that experienced morphological change over their lifetimes; what would happen if such machines developed as well as evolved? We don't yet know, but we're getting close. (Continuing our tongue-in-cheek naming convention, we could think of such methods as ''evo devo soro.'') Three years ago, Nicholas Cheney (Cornell University) and his colleagues introduced the evolution of soft robots. These robots were composed of a number of three-dimensional voxels, the number and position of which were determined by an evolutionary simulation. Moreover, evolution could dictate the material properties of these voxels: some were passive and stiff (a bone analog), some were passive and soft (a fat analog), and some actively increased and decreased in volume (a muscle analog). These and subsequent robots evolved by this research team were composed of many more voxels—hundreds in some cases—compared to the handful of rigid components found in Sims's virtual creatures. Although not the only reason, the softness of such virtual creatures may have eased evolution's ability to sculpt body and brain to yield desirable behaviors.

The future for this line of research seems wide open: evolution could determine not just the geometry and material properties of these machines, but how geometry and material properties change over the lifetime of an organism. Finally, evolution could determine which environmental signals affect such changes. One can envisage a soft robot that grows legs for walking in response to pressure on its feet, or grows fingers for gripping in response to pressure on its palms. At a finer scale, one could imagine local strengthening of appendages at exactly those points that experience the most mechanical loading, just as the initial attempts at walking attempted by young humans focus mechanical loading at their ankles, where bones ''hear'' this signal and respond by growing stronger. This line of research would thus take us from rigid robots to soft robots to deformable robots to adaptively deformable robots.

Once evolution discovers a general body plan and control strategy for robot movement, one can envision the deployment of a large number of identical robots into differing environments. Robots deployed in flat, wide open spaces may grow wheels, while robots deployed in canyons may grow legs. Such morphological plasticity would far outstrip that observed in animals, but some of the greatest triumphs in robotics to date involve discovering general principles (e.g., the aerodynamics of heavier-than-air flight) through observation of biological exemplars (e.g., birds) that leads to artificial exemplars (e.g., planes) and eventually superior artificial exemplars (space-going vehicles).

Despite our limited ability to manufacture physical versions of such machines, this journal contains many articles that suggest such a day is not far off. In the meantime, there are many gaps in our knowledge of ''evo devo'' that remain to be filled, as well as how to adapt such mechanisms to realize evo devo methods that produce plastic, adaptive, and useful soft robots.