

Using Biological Inspiration to Build Artificial Life That Locomotes

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Abstract. Nature's general principles can provide biological inspiration for robotic designs. Biological inspiration in the form of genetic programming and algorithms has already shown utility for automated design. However, reliance on evolutionary processes mimicking nature will not necessarily result in designs better than what human engineers can do. Biological evolution is more like a tinkerer than an engineer. Natural selection is constrained to work with pre-existing materials inherited from an ancestor. Engineers can start from scratch and select optimal raw materials and tools for the task desired. Nature provides useful hints of what is possible and design ideas that may have escaped our consideration. The discovery of general biological design principles requires a collapse of dimensions in complex systems. Reducing redundancies by seeking synergies yields simple, general principles that can provide inspiration. Even if we had all the general biological principles, we don't have the technology to use them effectively. Information handling has changed dramatically, but until recently the final effectors (metal beams and electric motors) have not. Nature will become an increasingly more useful teacher as human technology takes on more of the characteristics of nature. The design of artificial life will require unprecedented interdisciplinary integration.

1 Introduction

Evolutionary robotics appears to have evolved. The commonly held tenets now point toward the attainment of self-organized, autonomous, situated, interactive machines [7]. The field's collective focus seems to have progressed from a branch of artificial intelligence involving machine learning that was virtual to an emphasis on situated and embodied robotics [4]. Yet, within the field of evolutionary robotics at least three more distinct goals have been articulated [7].

Artificial Life. The artificial life community desires to create life-like creatures and life-as-it-could-be. Those attempting to create artificial life value full autonomy, self-sufficiency and self-containment. Many terms and concepts have been borrowed in part from the field of evolutionary biology in an effort to reveal

possible patterns of life. Obviously, this effort impacts algorithm development in fields of learning, adaptive control and optimization. By bringing novel ideas and methodologies, perhaps integration with evolutionary biology will lead to novel hypotheses for understanding the evolution and behavior of real life.

Assisting biologists with physical models. For centuries, biologists have borrowed ideas from physics, mathematics and engineering [24]. Truly remarkable discoveries have been made about how organisms work by developing testable hypotheses from knowledge in the physical sciences. Advances in the fields of physiology and biomechanics provide the most striking examples. In particular, the use of physical models to elucidate complex phenomenon still plays a major role despite our increasing capacity for accurate simulation. For example, the paradox of insect flight was resolved, not by solving three-dimensional Navier-Stokes equations, but by flapping scaled-model wings in a vat of syrup [6]. Our own research on legged locomotion has benefitted directly from the construction of several robots by providing us new hypotheses of control, stability and adhesion [8]. The use of physical models from evolutionary robotics directed toward the evolution and behavior of organisms promises to deliver novel hypotheses that may explain complex biological phenomenon. Attainment of this goal will continue to foster the exchange of ideas that will benefit several communities.

Attaining automated engineering. Artificial evolution can assist in automatically developing algorithms and machines that display complex, life-like capabilities that would be otherwise difficult to program [7]. Evolutionary techniques have been successfully applied in diverse areas such as network management, insurance, elevator operation, and circuit design. A more ambitious goal strives for “full autonomy . not only at the level of power and behavior, but also at the levels of design and fabrication”[18]. The justifications for using artificial evolution in engineering are varied. One extreme view claims that human engineers have failed and will continue to fail. “Robots are still laboriously designed and constructed by teams of human engineers, usually at considerable expense. Few robots are available because these costs must be absorbed through mass production, which is justified only for toys, weapons and industrial systems such as automatic teller machines [18].” The implication being that an artificial evolution approach would necessarily yield better results.

Engineers may not have created robots that operate as effectively as we have imagined or robots that are an economic success. However, the reliance on evolutionary processes mimicking nature will not necessarily do better. Biological evolution operates more on sufficiency rather than optimality. Engineers have distinct advantages over evolutionary processes. Secondly, an approach where biology inspires engineering holds greater promise. Biological inspiration involves the transfer of biological principles to engineers who are capable of capitalizing on them. Although nature is complex, general principles, rules and mathematical models can be extracted and novel designs characterized. Biological inspiration should include concepts from evolution, adaptation and learning. Thirdly, one of the reasons we may be dissatisfied with present day robots is that until now

nature could not be a very good teacher because human technology differed so from natural technology.

2 Evolutionary Tinkering vs. the Human Engineer

Biological inspiration in the form of methodologies such as genetic programming and genetic algorithms has already shown utility for automated design. However, reliance on evolutionary processes mimicking nature too closely will not necessarily result in designs better than what human engineers can do. It is important to be reminded that biological evolution works on the “just good enough” principle. Organisms are not optimally designed and natural selection is not engineering [14]. Engineers often have final goals, whereas biological evolution does not. Organisms must do a multitude of tasks, whereas in engineering executing far fewer tasks will do. As a result, “trade-offs” are the rule, severe constraints are pervasive and global optimality rare in biological systems.

2.1 Constraints and Biological Evolution

Biological evolution has brought us amazingly functional and adaptive designs. However, we must not forget that about five hundred million species have gone extinct and only a few million remain. Biological evolution works more as a tinkerer than an engineer [16]. The tinkerer never really knows what they will produce and uses everything at their disposal to make something workable. Organisms carry with them the baggage of their history. Therefore, they must co-opt the parts they have for new functions. Part of an ear is built from jaw bones and wings from legs. Organisms are not an optimal product of engineering, but “a patchwork of odd sets pieced together when and where opportunities arose” [16]. Natural selection is constrained to work with the pre-existing materials inherited from an ancestor. Dolphins have not re-evolved gills and no titanium has been found in tortoise shells [14]. Engineers can start from scratch and select the optimal raw materials and tools for the task desired, natural selection can not.

Organisms are not optimally adapted for the environment in which they reside. Biological evolution can’t keep pace with the changing environments because not all phenotypic variation is heritable and if selection were too strong it could easily produce extinction. Natural selection can’t anticipate major changes in environments. Behavior can evolve more quickly than morphology and physiology leading to mismatches. Engineers can optimize for one or a few environments and choose to add appropriate safety factors as dictated by previous experience.

Finally, most organisms grow, but must continue to function. As a result development can constrain evolution of the final product — the adult. Engineers are not so constrained and fortunately are not required to make fully function miniature versions of their final designs.

2.2 Nature's Role

Nature provides useful hints of what is possible and design ideas that may have escaped our consideration [24]. Given the unique process of biological evolution and its associated constraints, identifying, quantifying and communicating these design ideas is a challenge. Here is where the integrative biologist can contribute most to the inspiration transferred to the engineer. Biologists offering advice need not only understand principles of structure and function, but use their knowledge of phylogenetic analysis, behavior and ecology to extract potentially valuable design ideas. Design ideas motivated from nature should include those involving the processes of development, evolution and learning. However, engineers should not blindly copy these design ideas. In many cases, engineers have developed approaches, tools, devices and materials far superior to those in nature.

3 Biological Inspiration — An Example from Legged Locomotion

Nature's general principles can provide biological inspiration for robotic designs. The challenge is to discover them.

3.1 Curse of Dimensionality

The discovery of general biological principles often requires a collapse of dimensions because of the complexity of organisms. Behavior results from complex, high dimensional, nonlinear, dynamically coupled interactions of an organism with its environment. Given an organism's capacity for a multitude of behaviors together with the remnants of their history, we should not be surprised that animals show a remarkable degree of apparent redundancy when a single behavior such as locomotion is examined. Animals show kinematic redundancy for locomotion, because they have far more joint degrees of freedom than their three body positions and three body orientations. Animals show actuator redundancy for locomotion, because they often have at least twice as many muscles as joint degrees of freedom. Animals show neuronal redundancy for locomotion, because they have more participating interneurons than required to generate observed motor neuron signals. Reducing redundancies by a collapse of dimensions aided by seeking synergies and symmetries can yield simple, general principles. For instance, animals that differ in leg number, body form and skeletal type show the same dynamics of the center of mass [9]. All rapidly moving legged animals bounce like people on pogo sticks. Force patterns produced by six-legged insects are the same as those produced by trotting eight-legged crabs, four-legged dogs and running humans. Each animal has two sets of virtual legs that alternate. One leg of a humans works like two legs of a trotting dog, three legs of an insect and four legs of a crab.

3.2 Templates and Anchors

Fortunately, simple models we call *templates* can be made to resolve the redundancy observed [10]. A template is the simplest model with least number of variables and parameters that exhibits a targeted behavior (Fig. 1).

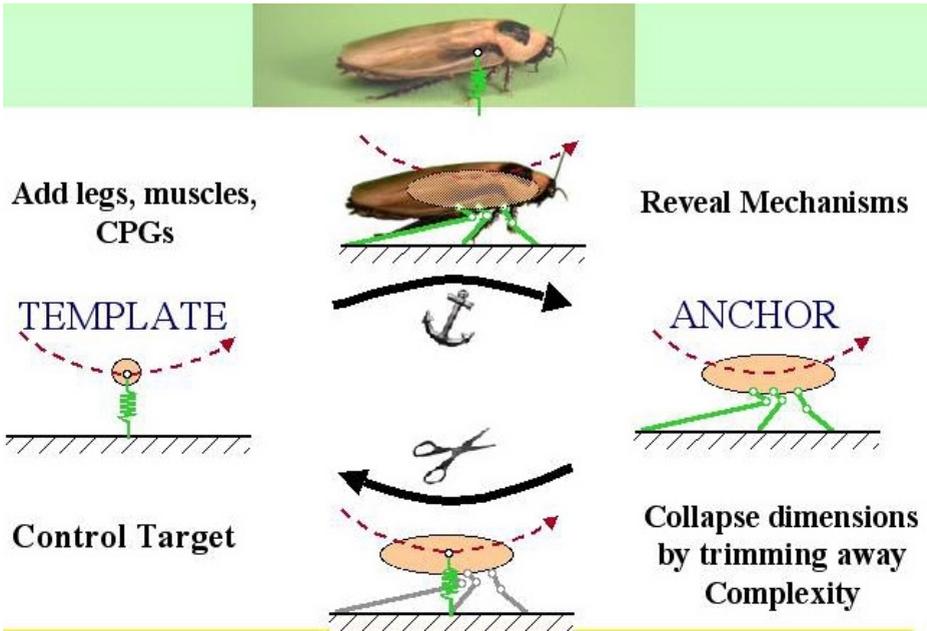


Fig. 1. Templates and anchors. The creation of templates and anchors for biological systems generates testable hypotheses that allow us to address the complexity observed in nature. This approach can be used to provide biological inspiration to engineers.

Templates suggest control strategies that can be tested against empirical data. Yet, templates must be grounded in more detailed morphological and physiological models to ask specific questions about multiple legs, the joint torques that actuate them, the recruitment of muscles that produce those torques, and the neural networks that activate the ensemble. We term these more elaborate models *anchors*. They introduce representations of specific biological details whose mechanism of coordination is of interest. Since mechanisms require controls, anchors incorporate specific hypotheses concerning the manner in which “unnecessary” motion or energy from legs, joints and muscles are “trimmed away” leaving behind the behavior of the body in the low degree of freedom template.

3.3 Evolution of Legged Robots

Ariel (Fig. 2 left) is an example of a biologically inspired robot (built by iRobot) benefitting from basic research on animals (conducted at UC Berkeley). This sprawled posture, hexapod is the only mobility platform that can move on land and maneuver underwater in the surf zone much like true amphibians - crabs [15]. To inspire the robot's leg design, we collected data on the morphology and kinematics of locomoting crabs [19]. We discovered joint synergies that reduced the degrees of freedom for each leg from nine to two, greatly simplifying actuation and control. We also found that crabs vary their stance width to reduce overturning moments when faced with a more variable environment. The use of a variable stance width in Ariel increased stability as well as adding the capability of obstacle clearance. Ariel also benefitted from behavioral observation of crabs on sand in the surf zone. To station keep, crabs oscillate their legs, dig into the sand and then generate a lateral gripping force. Ariel can use this behavior, but when its body surface orientation is unimportant it uses a decidedly, non-biological approach. If flipped over, Ariel simply inverts its legs and continues on.



Fig. 2. Biologically inspired robots. *Left.* Ariel. The first amphibious, legged robot capable of maneuvering in the surf zone. Built by iRobot in collaboration with UC Berkeley. *Right.* RHex, The robot hexapod capable of negotiating rough terrain using only six degrees of freedom, feed forward control and no external sensing of the environment. Built by University of Michigan and McGill University in collaboration with UC Berkeley.

Running insects operate as spring-mass templates [12,13] and use a largely passive, dynamic, self-stabilizing mechanical system to rapidly maneuver over rough terrain [17,22,23]. We have shown that the high dimensional space in which these agile, many-legged animals operate can be collapsed down to a few degrees of freedom, thereby simplifying control. Our findings inspired engineers to design and construct a dynamic hexapod, named RHex (Fig. 2 right), with only a six degree of freedom body forced by six passive, springy legs, each driven

by one geared DC servo [1,21]. RHex can maneuver over a forest floor, traverse sand dunes, negotiate rocks, climb over pipes and up stairs and even swim, all without feedback from the external environment.

4 Nature as a Teacher

If general principles can be extracted from nature, then why is there dissatisfaction with biologically inspired robots? As stated previously, a justification for primary use of artificial evolution for design and manufacturing points to the laborious efforts of engineers and the resulting financial burden. An alternative explanation lies in the difference in the technologies used by humans versus those observed in nature.

Nature will become an increasingly more useful teacher as human technology takes on more of the characteristics of nature [24]. Even if we had all the general biological principles, we don't have the technology to use them effectively. Information handling has changed dramatically, but until recently the final effectors (metal beams and electric motors) and sensors have not.

4.1 Human vs. Natural Technology

Traditionally, human technologies have been large, flat, right-angled, stiff, and rotating, with few actuators and sensors, whereas nature is small, curved, compliant using appendages with multiple actuators and sensors (Table 1, [24]). Human technology is changing with the greater use of nonmetallic, more flexible materials and increased miniaturization. Revolutionary new technologies in materials and manufacturing promises to lead to more life-like, mobile robots in the future when inspired by nature.

Table 1. Human vs. Natural Technologies

Human Technologies	Natural Technologies
Large	Small
Flat, Right-angled	Curved
Stiff	Bend, twist
Rotating devices	Appendages
Few sensors and actuators	Many sensors and actuators

4.2 Promise of New Materials and Manufacturing Techniques

Robots lack the robustness and performance of animals when operating in unstructured environments. However, even biologically inspired robot designs are compromised by the fragility and complexity that result from using traditional engineering materials and manufacturing methods. Clearly, designs must be

combined with physical structures that mimic the way biological structures are composed, with embedded actuators and sensors and spatially-varied passive properties. A new layered-manufacturing technology called Shape Deposition Manufacturing (SDM) makes this possible [3]. SDM's unique capabilities have resulted in a family of hexapedal robots whose fast (over 4 body-lengths per second) and robust (traversal over hip-height obstacles) performance begins to compare to that seen in nature (Fig. 3).

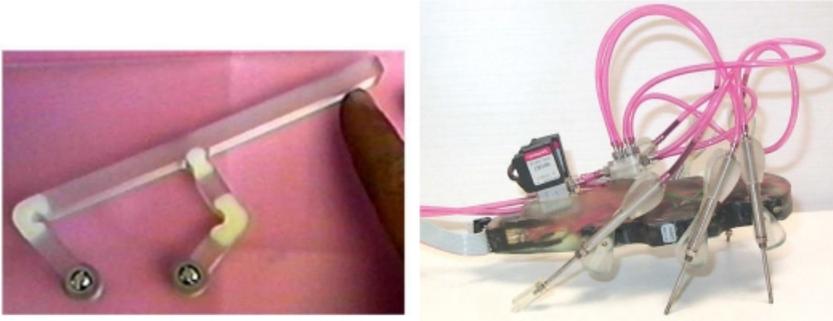


Fig. 3. Shape deposition manufacturing (SDM). Left. SDM compliant leg. Right. Sprawl. An SDM robot hexapod capable of negotiating rough terrain by taking advantage of the passive dynamic properties of its legs. No external sensing of the environment is required. Built by Stanford University in collaboration with UC Berkeley.

One major difference between animals and present day robots is found in the structure and performance of actuators. Animals use muscle, whereas most robots use motors. Muscle is a light-weight, multi-functional material. Muscles can function as motors, springs, struts and shock absorbers [5]. In collaboration with SRI International, we are currently measuring the muscle-like properties of electroactive polymer (EAP) actuators [11]. In these dielectric elastomers strain is induced through Maxwell stresses caused by the application of an electric field [20]. We have examined EAP actuators in the very same experimental apparatus in which we test natural muscle. We have discovered that acrylic EAP actuators produce stresses, strains, work and power outputs that fall within the capabilities of natural muscles.

Another extraordinary manufactured material that prevents almost any surface from being an obstacle to locomotion can be found on the feet of geckos. Each foot contains over 1 million tiny hairs arranged in rows [2]. Each hair can have as many as one thousand 0.2 micron flattened tips called spatulae. The nearly two billion spatulae allow such close contact with the surface that the adhesion force results from van der Waals interactions among molecules. Efforts are underway to use this inspiration to make the first self-cleaning, dry adhesive.

Research on gecko foot hairs did not originate with an effort to study adhesion. Instead, we were asked by a robotics company, iRobot, if we could provide biological inspiration toward the development of a climbing robot. We selected

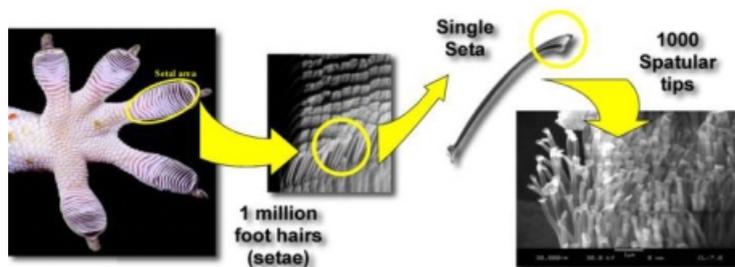


Fig. 4. Self-clearing, dry adhesive from gecko foot. Research a result of a collaboration among engineers and biologists from UC Berkeley, Lewis and Clark and Stanford University.

geckos because of their extraordinary ability to run up vertical surfaces at high speed. In doing so, we contributed to the evolution of an autonomous climbing robot, the first version of which was named the Mecho-gecko (Fig. 5). The success of the first clade of climbing robots was not due to the direct copying of the complex hair morphology, but was instead inspired by the observation that some geckos uncurl their toes during attachment and peel them away from the surface during detachment. By running geckos over a fancy scale (three dimensional force platform) imbedded in wall, we showed that large attachment and detachment forces were completely absent. By using this peeling strategy with a pressure sensitive adhesive, iRobot engineered two autonomous climbing robots. The next step is to evolve a robot with enhanced maneuverability for climbing. These robots will likely take advantage of legs and toes. In the future, we hope to evolve a climbing robot that will use the capacity offered by self-cleaning dry adhesives.

5 Age of Integration

Evolutionary robotics will continue to evolve. Biological inspiration can lead the way toward artificial life capable of extraordinary performance. Genetic programming, genetic algorithms and artificial evolution will continue to play a key role in the inspiration. Human discovery beyond artificial evolution will as well. Hopefully, we can direct artificial evolution along predominately productive lineages, and avoid the pitfalls so common in the history of natural life. Biologists working with engineers and mathematicians are discovering the general principles of nature from the level of molecules to behavior at an ever-increasing pace. Now more than ever before, nature can instruct us on how to best use new materials and manufacturing processes discovered by engineers, because these human technologies have more of the characteristics of actual life. This effort will require unprecedented integration among disciplines that include biology, psychology, engineering, physics, chemistry, computer science and mathematics. Fortunately, the age of integration is here.

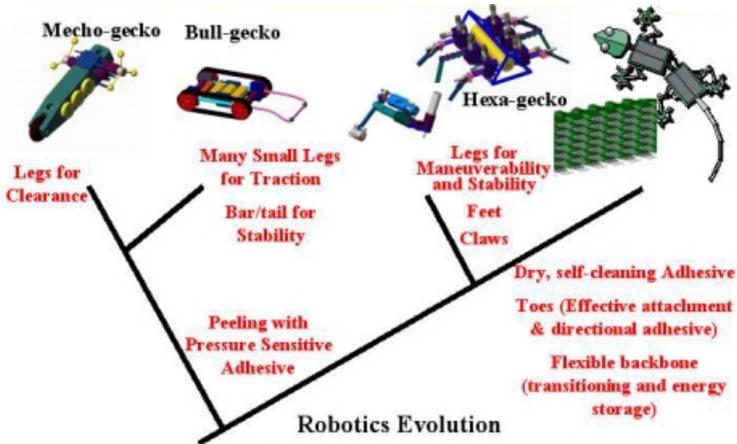


Fig. 5. Evolution of climbing robots. The evolution of the Mecho-gecko and the Bull-gecko included the innovation of using peeling with a pressure sensitive adhesive. The Hexa-gecko and Dry adhesive-gecko will be designed to use legs and toes. The Dry adhesive-gecko awaits the manufacture of the self-clearing dry adhesive hairs. Built or designed by iRobot in collaboration with UC Berkeley.

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