Bio-mimcry as a tool in the design of robotic systems

Jason G. Fleischer and Wade O. Troxell

Department of Mechanical Engineering
Colorado State University, Fort Collins, CO 80523

ABSTRACT

Traditional robot design methodologies often have problems dealing with dynamic and uncertain environments. Behavior-based robotic architectures have gained acceptance in the last ten years as a viable approach to this problem, but there are few formal design tools in the field. Designers often rely on their own experience or examples of similar systems to create a new robotic system. In many cases, the designers of behavior-based robots say they are inspired by a natural species accomplishing a similar task. These designers are trying to capture the dynamics of the natural system's task accomplishment, and re-create a qualitatively similar set of dynamics in the artificial system. Unfortunately, this process is ad hoc, not well understood, and still relies mostly on the experience of the designer. This paper presents a methodology for aiding the robotic system designer by mimicking biology, called biomimetic design. It examines the issues involved in designing a robotic system with biomimetic methods and presents an abstraction of the translation between the two worlds. This abstraction is used to better understand the process and pitfalls of re-creating the dynamics of a natural system in an artificial one, and to suggest a methodology for creating such systems. The methodology is demonstrated by the successful design of a cooperative system of six small mobile robots that find and retrieve ten target objects, of unknown location, in an eight meter by eight meter environment. The robots are designed to mimic the navigation methods of desert ants (genus *Cataglyphis*).

KEYWORDS

Bio-mimicry; Cooperative Mobile Robots; Biomimetic Robot Design; Foraging Robots; Cataglyphis

1. Bio-mimicry in robotic design

The servo-controlled robot to which we are accustomed is merely a type of automatic control system. At one level of definition, a robot is a type of automatic controller that is hooked to some physical component operating in the real world. This kind of system has been around since the Egyptians first built water-powered clocks and animated figurines 5000 years ago [1]. For hundreds of years before the invention of servomotors, cams and gears using electric motors, steam, or water for power actuated automated machinery. With so much design history behind us, you would be excused for thinking that we would be well versed in the best methods of designing such machines. But this is not the case. There are several ways that robot design can be viewed, and these methods do not always agree on what is important in designing systems. Many methods, such as classical control theory, have problems dealing with the dynamic and uncertain environments that tend to exist in the real world. One method that offers promise in dealing with such environments is mimicking biological systems that deal with tasks similar to the one the robot must accomplish.

Bio-mimcry is the process of taking inspiration, knowledge, or mechanisms from a natural system, which has some quality that we desire to emulate, to create an artificial system that has similar properties or dynamics. When bio-mimicry is defined this broadly, it is easy to find examples of it in many common scientific and engineering fields. Everything from Velcro to a neural network is biomimetic when viewed in this manner. However, when used in this paper, the term bio-mimicry will specifically mean a systemized and formal process of taking the dynamics from the natural world and translating them to the artificial one. This process can be captured in the transitions outlined below.

1) Problem definition ⇒ Useful natural system to mimic
2) Natural system ⇒ Model of the system's behavior
3) Model of natural system ⇒ Model of robotic system
4) Model of robotic system ⇒ Implementation

Each of the transitions above is a step in the process of biomimetic design. To be successful however, each one of the transitions should really be a mapping or translation from one paradigm to the next. Each translation should have a level of fidelity sufficient to ensure that the useful properties of the beginning paradigm, problem definition, are present in the ending one, implementation. Insuring the fidelity of the resulting translations is, of course, the hard part.

While following as exact a mapping from biology to the mechanical world as possible may yield a system with high fidelity of reproduction to the original, it may be too much. The dynamics desired might be captured with a much simpler model of the biological system. Control system theory uses this method often, modeling real non-linear systems with linear approximations.

For instance in foraging, several systems have tried to create a dynamic based on how some insects use a pheromone trial for navigation and as a means of encoding the location of interesting objects such as food. One low fidelity approach has been to use a chain of robots that forms a beacon path for guiding other robots in the same way that the pheromone trail guides the insect [2,3]. The opposite end of the spectrum is demonstrated by Kuwana, et. al. [4], who attached the living antenna of a male silkworm moth to a mobile robot, and demonstrated that it could follow a live female's pheromone trail. Somewhere in the middle lies the work of Russell, et. al. [5], who demonstrate a robot which follows a camphor trail by means of a gravimetric sensor crystal that can measure the deposition of the volatile camphor molecules on its specially treated surface. These examples demonstrate the range of possibilities when translating a biological system into the mechanical world.

2. Principles of bio-mimicry from existing robots

To better understand what bio-mimicry is, and how to use it as a robotic design tool, it will be advantageous to see examples of its use. In fact, biomimetic design has a long history in many fields, including robotics. This section will examine just a small sample of the many biomimetic robots and briefly mention some of the lessons to be learned from each experience.

In robotic design it is very common to mimic the physical abilities of a natural system, especially in the area of locomotion. In fact, many walking robots owe their designs to the field of gait analysis. Studies of the dynamic balancing methods used by various species have led to a host of walking machine designs [6,7]. These machines try to imitate the dynamics of a natural system as one *possible* means of providing support and mobility. Note that it is entirely possible to produce machines that are able to walk that have no parallel to any natural species. For instance, the Mars Micro-Rover consisted of two nested quadruped frames which could be lifted and translated independently [8]. The robot walked well, but there is no species that has a locomotion mechanism even close to it.

This is the first important principle of bio-mimicry for design: it does not generate unique or optimal solutions to a given task and environment set. Biomimetic design does, however, narrow down the range of possible solutions from the near infinite to a more manageable set. As a bonus, these solutions are known to work given the correct set of agent, task, and environment. Thus, if the translation can correctly capture the dynamics of the natural system, then the artificial design will also be able to complete its task reliably. This illustrates the importance of the translation and the how important it is to understand its nature, as was discussed in section one.

The coupling of sensing and locomotion is a more involved use of bio-mimicry. A robot developed by Morse, et. al. [9], exhibits this kind of bio-mimicry by copying the chemotactic food-searching dynamics of a soil nematode. By closely examining the interaction of the nematode with its environment, they were able to characterize the nematode's food-searching dynamics as consisting of three essential parts:

1) The animal detects chemical gradients by means of a point sensor located on its head and making temporal comparisons of the local concentration.
2) The direction of movement and rate of turn of the nematode is controlled by the angle of the head with respect to the body.
3) The nematode moves at a nearly constant speed during chemotaxis.

Morse, et. al. determined that these essential dynamics allowed them to construct a four-wheeled robot with Ackermann steering, constant velocity motors, and a single photocell that would have the same dynamics in phototropism as the nematode did in chemotaxis.

How where they able to make such a drastic simplification and still have the system exhibit the same dynamics? The mechanistic view of animal behavior holds that sensing is tightly coupled to action. For an animal the perception of action leads directly to the action on the part of the robot. That is, it is important to study what an animal can perceive about its environment and how that perception triggers action [10,11]. By studying and properly describing that interaction, the solutions to mimicking the behavior may become obvious and simple. Thus, a second principle of biomimetic design is to examine closely the fit between the animal and its environment to find clues that will lead you to the basis of its behavior, and how it can be re-created in the robot.

Artificial Neural Networks (ANNs) are a particularly successful form of bio-mimicry. ANNs are models of biological neural networks, which have the ability to decompose complex information, in parallel, into basic elements. In this manner neural networks can react to input much faster then a sequential microprocessor which operates at a switching speed many orders of magnitude faster. There are several different models of ANNs in use to mimic the activity of biological neural networks. However, the primary differences between these models are items such as the number of layers of the network, the learning algorithm, and how the neurons can interconnect. Almost every model shares the same concept of an individual neuron. The neural model's transfer function is [12] $O_i = F_i\left(\sum_{j=1}^{n} w_{ij}x_{ij}\right)$, where the neuron's firing condition is $\sum_{j=1}^{n} w_{ij}x_{ij} \geq \Theta_i$, index i represents the neuron in question, Θ_i is the bias term, F_i is the thresholding function, and index j represents the inputs from other neurons.

This model has fundamental differences from the way a real biological neuron acts. Biological neurons do not output a steady value, instead their outputs come in the form of pulse trains of varying frequency. Additional complications come from the synaptic connections between neurons, where the electrical pulses become chemical signals flowing across the gap. For instance, the synaptic efficacy changes as a result of the amount of activity, strength, and frequency of stimulation. Finally, many ANNs use very simple non-linearities for F_i to make analysis easier. One very popular non-linearity is a simple "on or off" threshold function which lacks all intensity information present in real neural structures. Only a few attempts, such as [13] have been made to create a more realistic neural model.

In spite of the many differences between ANNs and their biological counterparts, neural networks are a popular and useful solution to many difficult problems in control, signal processing, and data processing. In other words, even though ANNs don't operate at a very high level of fidelity they are very useful models. Why then, are ANNs such loose translations? Because that is the level human understanding and technology can cope with. In order to build a more faithful reproduction, one might need to either build a full-blown simulation of all the molecules involved or actually grow your own biological neurons. Thus, we end up with such low fidelity elements as threshold non-linearities. This is a third important principle of biomimetic systems: fidelity can only be as good as human understanding can make it. One must then build the system to find out if the level of fidelity possible is actually useful.

Another example of robotic bio-mimicry can be found in the design of various behavior-based control architectures. Behavior-based approaches to robotic control are believed to more closely approximate how animals make decisions and choose actions in their environment. The fields of ethology and environmental psychology both attempt to describe animal actions in terms of behaviors, which are generated by the perception of releasing mechanisms or affordances in the environment. Various control architectures have been proposed to make robots reactive to their environment in this same way.

For instance, Connell's colony-style architecture [14] addresses the need to integrate a large number of functions and select the appropriate action. The original subsumption architecture design had a web of interlocking behaviors, which were difficult to expand without modifying the already existing structure. Connell addressed this problem by eliminating direct communication between various behavior modules. That is, the only way in which various behaviors communicate is through changes they can mutually observe in the environment. This architecture also eliminates any concept of long-term state information. Thus, the robot is completely immersed in its environment and selects actions only by what it currently knows about the world. It also enables the robot to be endlessly expandable without having to redesign the parts of the controller already in place.

These points bring us to a fourth principle of biomimetic robots: make sure that the components of the systems can be integrated into a whole. Unwieldy and poorly thought out methods can seriously hinder the modification and expansion of the system.

Finally, the amount of complexity needed to accomplish a given task can be located in either the design of the robot or in the structuring of the environment. For instance, two possible approaches to solving a navigation task include using a complex vision system for recognizing landmarks, or placing a set of barcodes at known locations in the environment that the robot could read and triangulate from. Similarly, such complexity once located in the robot can be distributed between mechanical design and controller architecture. For instance, a hexapod walking robot traditionally has some multiple of six actuators, which require complex controllers to synchronize properly. However, one Colorado State entry into the 1999 Walking Machine Decathlon uses a mechanism that utilizes two actuators running parallelogram four-bar mechanism legs through a system of spur gears [15]. In this way, it relocates much of the complexity of hexapod gait from the controller to the mechanical design of the legs.

3. The biomimetic design method

The biomimetic design method comes in two parts: process and principles. By following the process and applying the principles described above, a system can be designed using this biomimetic design method. The method is described in Tables 1and 2.

A few more comments should be made on applying the biomimetic design process. As mentioned previously, biomimetic design does not necessarily yield an optimal design. When working in such a design space it is futile to try to optimize the design. Instead, the designer should concentrate on making the design "good enough." If the design fits all the reasonable performance criteria laid out in the problem definition then it is a successful design.

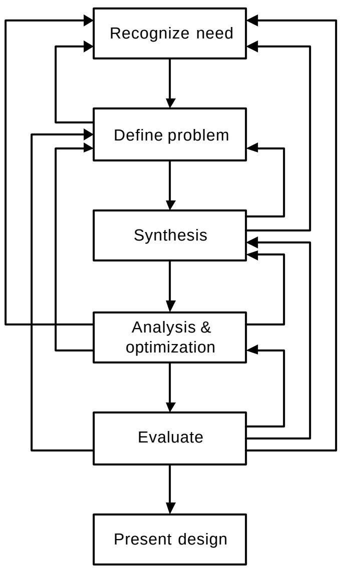

Figure 1. The traditional model of engineering design, which is complemented and not replaced by the biomimetic model of design presented here.

Note that this method of design does not replace the traditional model of engineering design, such as illustrated in Figure 1. Rather, it provides a framework inside it, giving the designer guidance that might prove valuable in creating a workable and robust design. In fact, steps two through five of the biomimetic design model become the synthesis step of the traditional design model, and steps one and six take their respective positions in problem definition and analysis.

Table 1. The principles of the biomimetic design method

Principles	
I.	It is important to maintain enough fidelity in each translation that the dynamics desired are maintained, but not so much that it overwhelms the understanding and technology of the designer.
II.	An agent (robotic or natural), its task, and environment are an inseparable trio.
a.	When analyzing a system, decomposing the relationships between the agent/task/environment trio is critical to understanding its function.
b.	When designing a system, it is important to remember that any one of the trio can be designed, not just the robot.
III.	The design architecture must allow for the re-assembly of the deconstructed parts back into a useful and synergistic whole.
IV.	Complexity in the system can be traded-off between various components, such as robot and environment.

Table 2. The process of the biomimetic design method.

Procedure		
Step	Comments	principles used
1) Define the problem	Try not to over-constrain the problem unnecessarily, it will restrict the design options available.	IIa
2) Find a useful natural system to mimic	Ethology, ethnology, sociobiology, and environmental psychology are all useful fields to find information from. If more then one system fits the problem definition use the one which has been studied the most.	I, IIa
3) Create a model of the natural system's behavior	Preferably this is merely a matter of finding such a model from the literature, and the designer won't have to do this from scratch.	I, IIa
4) Translate the model of the natural system into a robotic model.	In this step principle I has to be carefully balanced against technical and economic feasibility.	I, IIb, III, IV
5) Implement the robotic model in a real system	Experience in this step will lead you to create more realistic models in the first place, reducing the number of times iteration will take place between steps 4 and 5.	I, IIb, III, IV
6) Analyze the robotic system and make sure it meets the problem specification sufficiently.	Iteration may be necessary back up to any step in the process if it fails to do so.	IIa

4. A cooperative mobile robot system designed with the biomimetic design method

The biomimetic design model developed in the previous section was applied to create a real robotic system. A very brief outline of the design and the testing of the system is presented here. However, a more complete version of the system design, its testing, and how the biomimetic design process was applied can be found in [16].

Problem definition

Robot, task, and environment are an irreducible trio; therefore the problem definition includes aspects of all three. Six Talrik Junior robots from Mekatronix were modified to allow them to accomplish a foraging task. The robots consist of two-wheeled holonomic bases, 18cm in diameter and 8cm tall, controlled by a Motorola 68HC11. The robots already posses tactile and IR obstacle avoidance sensors. The foraging problem involves finding and retrieving ten 30mm wood cubes back to a home base. The robots have no explicit model of the nature of the environment or the location of the target objects. The environment is an indoor carpeted area eight meters by eight meters, enclosed by a white wall. There is a 60cm x 60cm home base marked with reflective tape located in the middle of the enclosure. Rather then randomly distributed through the environment, the target objects are in a randomly placed clump of about one meter by two meters in order to simulate the nature of tasks such as cleanup, harvesting, search and rescue, and planetary exploration and sample retrieval.

The biomimetic cooperative mobile robot system

Saharan desert ants, of the genus *Cataglyphis*, utilize a polarized light compass and optic flow to determine their position approximately [17], then increase their certainty using learned landmarks [18]. *Cataglyphis* is unlike other ants; it does not use pheromone trails for navigation or recruitment for food sources, but relies solely on the navigation method outlined above. They also do not communicate explicitly with each other about the location of food sources. Rather, they use a strategy where each individual ant pursues a favored search direction from the nest. If it does not find food in this direction after a certain time it will return home and try a slightly different direction [19,20]. In this way the resources of the colony are divided up efficiently by each ant acting on only the information that it can sense directly. These characteristics, combined with the fact that these ants are well studied, made *Cataglyphis* a suitable choice for the task desired. The robotic system designed mimicked the path integration navigation and search direction selection aspects of the ants foraging behavior to solve the problem defined above. It did not, however, mimic the ant's ability to use landmarks to localize its location and develop memorized paths to its nest. This was beyond the capability of the robotic platform.

The TJ robots were programmed to implement the *Cataglyphis* style foraging in a behavior-based subsumption architecture. The TJ robots were also physically modified to be able to implement the required behaviors. Instead of a polarized light compass the robots were equipped with a digital magnetic compass which could differentiate between eight headings, i.e. it could tell north from northwest, from west, etc. In order to determine distance traveled, the robot uses a timing system and the speed commanded to the motors. A gripper to manipulate target objects was designed and implemented along with a tactile sensor to determine when a target object was present in the gripper. Finally, a downward pointing reflective infrared transmitter and sensor pair could determine when the robot was at home, since the home base was marked with reflective tape on the floor.

Experimental results

The foraging experiment was run for a relatively short duration in order to make the task as challenging as possible. With 64 square meters of area to cover, even following an optimal search the six robots would require approximately seven minutes to completely search the environment. Since the resulting search is far from optimal, and the robots then have to contend with navigating home, it is not surprising that there were no returns of target objects to home base during these short experiments. However, the navigation system did prove quite successful in its task, and a look at Figure 2 shows promising signs for future fine-tuning of the design.

Generally, there were two types of foraging trips. In the first, the robot's navigation system would function with sufficient accuracy that it would simply make its outbound search and return directly home, perhaps after a short spiral search. This occurred on roughly one third of the trips. The second type of trip occurred when the accuracy of the navigation system was not sufficient and the robot executed long spiral searches after originally missing the location of the home base. In these cases, the robot would return after wandering around the environment from two to seven minutes.

Total time elapsed (min)	17
No. of successful navigation returns by a robot	17
Time normalized average navigation success rate (robots returned per min)	1
No. of approaches within 1m of the center of home base	31
No. of target objects picked up	9
No. of target objects retrieved	0
No. of approaches within 1m while carrying a target object	3
No. of times a robot physically interfered with another robot	19
No. of target objects knocked out of the gripper by collision	7

Figure 2. Combined results of several experiments with the robotic system.

Robots collided with each other on a regular basis. The obstacle avoidance sensors and behaviors, which were not biomimetic, did not function well enough to keep the robots from colliding with each other or other obstacles. In several instances, these collisions stripped target objects from the grippers of the robots. Do to the nature of the control algorithm these robots were unaware of this circumstance and continued to behave as if they possessed the target objects.

5. Conclusions

The values shown in Figure 2 suggest that small modifications could significantly increase system performance. The numbers indicate that if a beacon system with a one meter range were installed the navigation success rate might increase by nearly a factor of two. An increase in successful navigation rate could help alleviate the lack of successful target object returns. This result is actually encouraging for the biomimetic design method. Because of technical constraints, no landmark recognition abilities were included in this robotic system. Even though it is possible to draw a parallel between this configuration and a new forager, it is still a lower fidelity form of bio-mimicry. In fact, research has suggested that robust animal navigation is composed of path integration, landmark recognition, and the use of canonical, landmark-referenced paths [21]. By extension, robot navigation should be composed of those same components, but in this case only the first one was present. Therefore, some validity is conferred on the biomimetic design method, since it accurately predicted that fidelity would be a central issue in achieving a robust design. A higher fidelity biomimetic design would probably have fared better.

The biomimetic design method developed here was a useful tool in creating a cooperative mobile robotic system for a foraging task. The biomimetic design method aided in both conceiving of a design capable of solving a given problem, and in implementing that design in a robotic system. In this case following the method successfully allowed the designer to create a workable real world system – the ultimate goal of robotics.

However, the proposed method is not without its pitfalls and problems. As it exists, there is little it can say about quantities rather then qualities. While it is known that the fidelity of a translation is important, there is no way to figure out just what level of fidelity is needed in any given situation. Nor are there any ways to know what parts of a biological model may safely be excluded and still create the dynamic desired.

What the biomimetic design method offers most of all is guidance and the beginnings of formalism. To create highly competent robots in a reliable manner a science of robot design is needed. Such a science would consist of a knowledge base and a set of principles that could be used to explain and/or predict the behavior of robotic systems. While the method proposed here is a long way from such an achievement, it does provide a possible framework for viewing robotic system design. If the abstraction presented here turns out to have merit in design practice, it could be fleshed out into a more useful form by continued research.

Future work on this method could pursue either empirical or theoretical paths. More complete surveys of existing biomimetic robots and further experiments with new ones could reveal new principles of biomimetic design or suggest changes to the method itself. Theoretical work on more realistic modeling of robot/task/environment interaction and advances in understanding the neural basis of behavior would also have significant impact on the development of the biomimetic robot design methodology.

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