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Mathematically characterizing natural systems for adaptable, biomimetic design

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Abstract

Biomimicry, used increasingly to make engineering advances, remains underutilized on the scale of the built environment. Drawing from a systems engineering foundation, this research characterizes biomimetic design by the natural principle *form follows function*. By identifying and manipulating the mathematical functions that govern the resulting natural form, this research explores how built structures can best capture the fundamental functions of an organism. Studying an organism's form, processes, and habitat can lead to the development of structures that are able to adapt to changing trends and standards over time. An example is provided from the authors' current project, which involves structurally modeling the *Turritella terebra* seashell and conducting parametric studies to determine which of its characteristics allow for its adaptability. These adaptability parameters can be mapped to analogous characteristics in structural design.

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1. Introduction

Biomimicry is a design method that draws on the inspiration of Nature for more sustainable solutions to human challenges. Nature has 3.8 billion years' worth of time-tested patterns and strategies, which engineers can learn from

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and apply; many human problems have already been faced and resolved in one form or another in Nature. For the sake of organization, behaviors of natural systems are broadly generalized into ten principles [1], which cover concepts such as an efficient use of energy and resources, the recycling of all materials, system resilience, and optimization and cooperation, among others.

One principle that is of particular relevance for adaptable infrastructure design is *form follows function*. While this phrase is widely recognized as originating from modern, industrial architecture (20th century), this concept draws from the theory of evolution (e.g., as described by the overlap in Lamarck and Darwin's theories in the 16th-17th centuries). Nature shapes its structural forms to help meet functional requirements, rather than adding material and energy to produce similar outcomes [1]. Natural structures are honed and polished through natural selection, resulting in systems that are effective, efficient, and multifunctional to meet each organism's performance demands [2]. When abided by, this principle carries potential for a more sustainable built environment.

The term *bio-inspiration* has been popularized in many disciplines, and as the term suggests, designers often draw qualitative, conceptual ideas from Nature. While biomimicry suggests an inherent quality of sustainability in a design, bio-inspiration is a term which encompasses a broader source of creativity (e.g., biomorphism, biophilia, and bio-utilization, which are all forms of bio-inspiration, but are not intrinsically sustainable) [3]. The next step in biomimicry research and practice is to add rigorous quantitative analysis to justify and support biomimetic designs for sustainability.

Using structural engineering tools and methods, our research explores natural systems through a bottom-up approach to reveal system properties of organisms. By pinpointing which emergent properties are the root of structural form, we have the opportunity to create simplified models of complex systems that are mathematically based. In other words, we can better understand the mathematical functions underpinning natural forms, and vice versa.

In this paper, we explore the principle of *form follows function* in common systems from various engineering disciplines. To describe the physical behavior of a system, a mathematical model called a *governing equation* is often used [4]. Governing equations are frequently seen as differential equations obtained by substituting a system's constitutive relationships into more general laws of physics. For example, the governing equations of mechanical systems are expressions of Newton's Second Law, while those of electrical systems are representations of Kirchhoff's Voltage and Current Laws. In these sorts of analyses, we are primarily interested in a system's behavioral response to various inputs. By extrapolating this idea of mathematical description to natural systems, our research investigates the effect of organisms' structural parameters on adaptability over time.

1.1. Governing equations of woodpeckers and harmonic oscillators

In classical mechanics, the dynamic motion of a system can be characterized by three simple elements: a spring, a mass, and a damper. Modeling a mechanical system with these parameters enables representation of not only its potential energy and energy dissipation capabilities, but also captures intrinsic characteristics of the system, such as its natural frequency, and consequently the time it takes return to a steady state response after a disturbance. Understanding this level of detail is important in many structural applications, as unintentionally vibrating a system at its resonant frequency can cause catastrophic failure (e.g., Tacoma Narrows Bridge collapse in 1940).

The dynamics of many mechanical systems can be characterized as harmonic oscillators, which is a system that experiences a displacement and fluctuates around its equilibrium point. Depending on the values of certain parameters, a system can exhibit various response behavior. For example, the sole value of the damping ratio (a constant dependent on the physical specifications of the spring, mass, and damper) can determine whether the system will return to a steady state value without oscillating past its equilibrium point, or if the system will return to a stable configuration at all. In cases with a driving force, oscillation amplitudes may even gradually increase until overwhelming internal forces cause the system to fail.

The governing equation of harmonic oscillators is often portrayed as

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{1}$$