Analysis of Biomimetics in the Application of Robotic Locomotion with a Focus on Structures, Materials and Dynamics

By

Ari Parsons Miller

Submitted to the
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in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

Biomimetics is the study and analysis of natural systems to inform engineering design and technology development. Through interdisciplinary research and analysis of natural phenomena, engineers are able to gain valuable insight to drive efficient and robust innovation. A critical understanding of nature's design constraints is necessary to effectively create an optimized bio-inspired design. A literature review of bio-inspired design is conducted with a focus on structures, dynamics and materials in the context of robotic locomotion. The biomimetic process in the read literature is analyzed for procedure and accomplishment. A generalized method of biomimetics is presented, based on the studied work. It is concluded that successful biomimetics requires four key elements: (1) a clear understanding of the natural system, gained through depth of biological study, (2) the development of a simplified model that encompasses the core elements of the natural system, (3) the design of a synthetic system that meets the model's specifications, and (4) engineering optimization to improve the final design.

Thesis Supervisor: James H. Williams
Title: Professor of Mechanical Engineering, Writing and Humanistic Studies

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Introduction

Biomimetics is the study and analysis of natural systems to inform engineering design and technology development. Nature has developed its own method of design optimization, employing natural selection to improve organisms' survivability. By better understanding the challenges faced by nature, we have the opportunity to learn from the solutions devised through evolution's billions of years of R&D. Most engineering challenges have already been confronted by nature. It would be unwise to overlook such opportunities for design inspiration.

Affecting such varied applications as solar arrays, prosthetics, architecture, cosmetics and computer programming, biomimetics can arguably be applied throughout all industries. A great example is Velcro, shown in Figure 1, a method of reversible adhesion inspired by the tiny hooks of burdock burrs.

Figure 1: The hooks and loops of Velcro are able to grip upon contact, much like burdock burrs snag on to the fibers of hair and clothing. [1]

Biomimetics supports the sharing of perspectives between biologists and engineers, fostering interdisciplinary collaboration. The sustainability and energy efficiency of natural systems also offers insight into ways to improve environmentally aware design and waste reusability.

It is important to acknowledge that biomimetics is not simply the act of mimicking biological systems. It requires thorough study of living organisms and the environment in which they effectively operate. Without such research, the usefulness of similar mechanisms in a synthetic system cannot be truly understood.

To extract design inspiration from a natural system, nature's constraints and goals must be compared to those of the engineer. Natural systems are complex and multifunctional, while engineering applications generally have a few very specific objectives. While some biological functionality becomes clearly irrelevant to the engineer, such as procreation and digestion, it is not an easy task to simplify a natural system into its core components. However, this is a critical element of effective biomimetics.

By modeling a simplified abstraction of the desired biological mechanism, the designer can hope to derive the essential components needed to achieve the functional goal of his or her synthetic system. Then, moving away from mimicking biology and towards engineering design, the synthetic system can be further optimized through prototyping and engineering iterations. Once the key elements are understood, a better design than the original biological system can often be engineered.

One limitation faced in bio-inspired design is the capability of current manufacturing technology. Nature assembles materials with complex geometries and physical properties, using cells as its microscopic building blocks. Natural materials often have variable stiffness and damping, with components integrated into a unified whole. In standard production, materials are generally isotropic and methods of shaping and joining do not allow for such intricacies as are found in nature.

Rapid prototyping technology such as 3D printing and shape deposition manufacturing (SDM) begins to offer greater design flexibility, but it is expensive and still limiting. SDM makes it possible to manufacture parts with multiple materials and embedded components. SDM consists of a cycle of depositing structural and filler materials. Between each layering step, the part can be machined to the desired geometry. Components such as sensors or stiffening material can be inserted before a new layer is added [2]. This process is shown below in Figure 1.

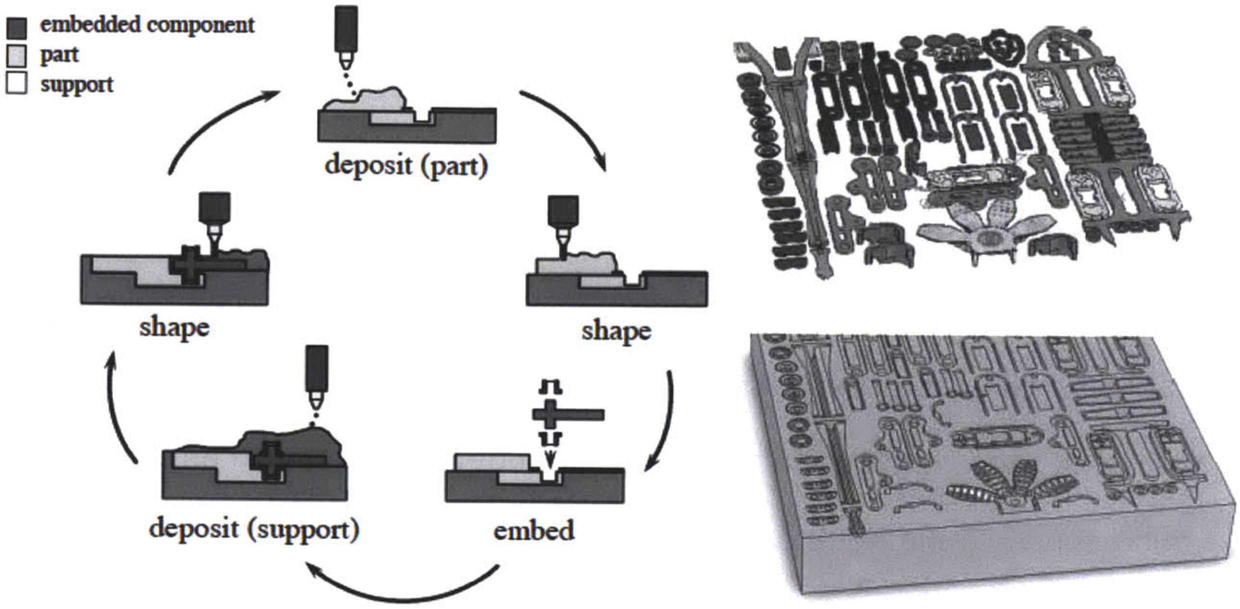


Figure 2: Shape deposition manufacturing is a process that involves the alternate layering and shaping of structural and filler material. Discrete components can be added after any shaping step. Multiple components can be fabricated on the same substrate. [2]

As technologies like SDM are integrated with large-scale rapid prototyping techniques, we will see a greater ability to mimic the sophisticated materials and integrated design of natural systems.

Through a literature review of current research, bio-inspired design was examined as an effective method for improving performance in robotics applications. With a focus on structures, materials and dynamics, the research publications studied involved robotic movement inspired by animal locomotion. The majority of read papers were published in the journal *Bioinspiration and Biomimetics*. By observing the depth of biological analysis performed by the researcher, the potential for optimization of their final design is assessed. A generalized method of biomimetics is then presented, based on the reviewed literature.

Reviewed Works

Nature-inspired flight

In this editorial article, *Lentink and Biewener* give an overview of multi-faceted flight control mechanisms used in nature [3]. Independent evolution of many different species has created a variety of interesting methods of flight, which offer potential application in engineering design. Published in *Bioinspiration & Biomimetics* alongside papers describing specific bio-inspired engineering research and development, it offers a valuable synopsis of where such 'airborne' research has been heading.

Bird wing design and control can offer extensive inspiration for engineering flight systems. The airplane clearly takes the profile of a soaring bird, but the bird's flexible flapping wing has not been effectively implemented in modern aviation applications. However, it is interesting to note that the Wright brothers' first aircraft used wing-twisting mechanisms to bank in flight much like a bird [1]. As manufacturing methods allow for greater freedom of design, the potential of flexible wings in flight-worthy robots will increase, allowing for much greater maneuverability. *Grant et al* explore the use of flexible wings in the design of a micro air vehicle in a later article analyzed in this thesis [4]. Current research also explores how birds achieve flight stability without a vertical tail (as most conventional aircraft rely on). One challenge of the study of birds to influence large aircraft design is the change in flow characteristics as described by the Reynolds number *Re*,

$$Re = \frac{\rho L v}{\mu} \quad , \tag{1}$$

where ρ is the density of air, L is the characteristic length, v is the velocity of the bird or plane in relation to the air, and μ is the air's viscosity. A high Reynolds number means that inertial forces are overpowering viscous forces, causing turbulence. Birds operate at a much lower *Re* than conventional airplanes, due to their smaller size (lower L) and slower velocity. While birds are expert flyers, due to this disparity, their flight mechanics cannot be directly applied to large, high speed aircraft [3].

Many birds utilize thermals, rising columns of warm air, to save energy in gaining altitude. To find thermals, it has been speculated that birds are able to sense changes in airflow across their wings through mechanoreceptors near the follicles of their feathers. By sensing pressure changes at the boundaries of thermal updrafts, a bird is able to efficiently utilize the area of the air column [3]. It is easy to see how such receptors could be utilized in small robotic air vehicles.

While natural flight may seem synonymous with the winged bird, there are many other mechanisms that various animals and plants use to control airborne movement. Geckos are able to use their tails during a fall to control body orientation. This has inspired the use of inertial appendages to manage flight control under challenging conditions where lift control mechanisms may not be as effective. Some snakes are able to jump from a high perch and slither through the air to extend the trajectory of their fall. This undulating motion during descent could expand the capabilities of robots of snake-like design [3].

On another end of the spectrum is the maple seed, utilizing a single 'wing' to manage its flight path from tree to ground. The maple seed's rigidity gives likeness to stiff airplane wings and helicopter rotor blades. Through the study of the maple seed's dynamics during descent, an at-scale robotic maple seed was developed, shown in Figure 3. Climb rate and transverse movement are controllable through variation in wing pitch, offering a simplified alternative to helicopter flight control and a design opportunity for micro-helicopters [5].

Figure 3: At-scale robotic maple seed developed by *Ulrich et al*. [5]

Biomimetic joints for morphing of micro air vehicles

While micro-air vehicles have become common in recent years, their limited ability to handle challenging environments and flight conditions has prevented their use in most real-world applications. While small, agile aerial vehicles give the opportunity for use in areas with dense obstacles, the current technology cannot handle swift maneuvering and strong wind variability. This research uses pivoting mechanisms to allow for flexible wings, drawing inspiration from the laughing gull, *Larus atricilla*. The constructed aircraft were of similar size and shape to this species of gull, and incorporated an elbow and wrist along with full wing twisting [4]. The wing morphability *of Larus atricila* can be seen in Figure 4.

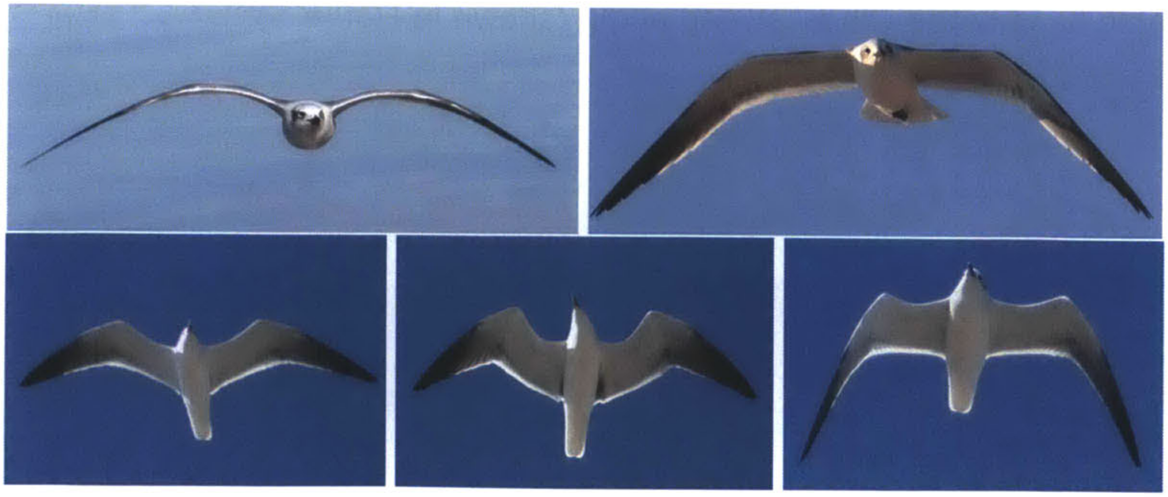


Figure 4: Wing morphing of *Larus atricilla* in flight, using elbow and wrist joints at the root and midspan of the wing, respectively. [4]

The ability to morph flexible wings allows for birds to optimize their aerodynamic efficiency, reducing the muscular energy needed to maneuver. By wing morphing, gulls are able to control flight parameters such as glide speed, longitudinal pitch stability and lateral yaw stiffness. A large range of wing configurations are possible by managing dihedral and anhedral angles at the root and elbow of the wing. Asymmetric configurations are also possible, allowing for tight turns and crosswind flight [4].

The researchers model the bird wing bone structure as a two-jointed arm, based off of three-dimensional scanning of several bird species' wings through the flapping cycle [4]. Two aircraft were then designed and constructed. Both were of similar size and weight to the laughing gull. The first aircraft was designed for gull-wing morphing, with wings able to rotate at the base and elbow. The second aircraft is able to vary the wings' sweep angle (shown in Figure 5).

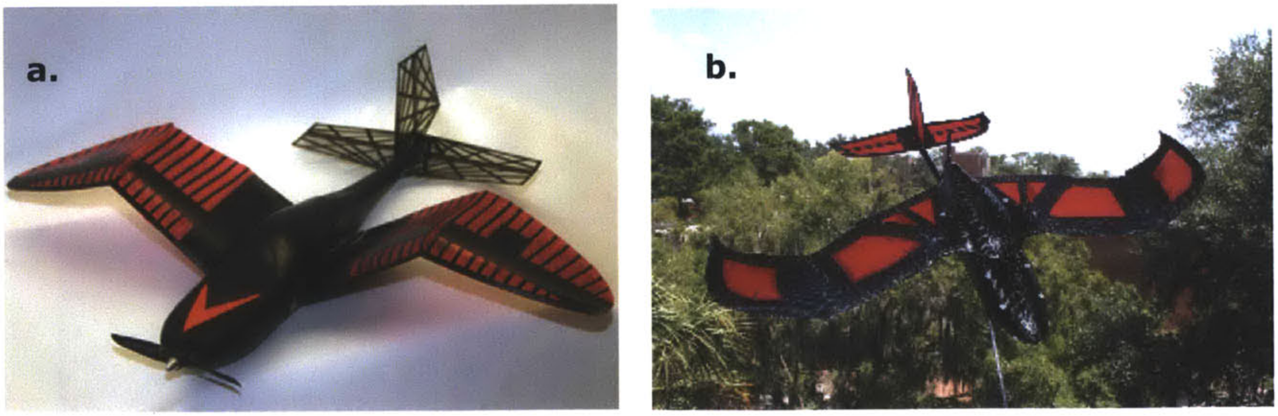


Figure 5: The two aircraft modeled after the laughing gull, *Larus atricilla*, with wings capable Of (a) dihedral angle variation and (b) sweep angle variation. [4]

Through experimentation, the effect of wing morphing on flight performance was isolated and tested under various conditions. Through future work, the development of an aircraft combining the sweep and dihedral wing morphing is planned [4].

A concern with the methodology of this research is the relation of the biologically-inspired aircraft design to the desired aircraft performance. While the *Larus atricilla* was modeled by flapping wing geometry, the testing and flight performance of interest involved maneuvers involving dives and tight turns. It is not directly clear that nature's optimization of the bird's wing flapping is relevant to the wing's performance in these maneuvers. Inquiry into the wing dynamics during such maneuvers may provide further insight into the researchers' micro air vehicle design goals.

The biomimetic success of this work is in the design and analysis of the gull-wing-inspired robotic aircraft. A greater depth in background research and modeling would provide insight in aircraft design, but much will still be learned from the future flight studies of this system. With manufacturing challenges and differences in control mechanisms between birds and robotic aircraft, this work does not seek to stray far from conventional plane system architecture. This yields a safer response from industry, but a lower chance of achieving the full potential of biomimetics. However, as the engineering design is optimized, it will have the opportunity to reach commercial application more quickly if it meets many of the same specifications as similar aircraft, which is a strong benefit of this strategy.

Modeling locomotion of a soft-bodied arthropod

The authors of this work are interested in the locomotive mechanisms of highly deformable animals to inform the design of compliant, underconstrained robots [6]. Caterpillars are able to move over complex terrain in any orientation, as well as burrow several body lengths into soil. Through the study of the soft-bodied tobacco hornworm caterpillar, *Manduca sexta*, a simplified kinematic model of caterpillar gait was constructed. By comparing computed ground reaction forces from this model to collected experimental data, the researchers validated the model's ability to describe caterpillar crawling [6].

Before this work, the tobacco hornworm caterpillar's muscle structure was well understood. *Manduca sexta* has 16 distinct segments, each containing more than 70 muscles. The caterpillar uses ten prolegs along its abdomen to passively grip its climbing surface. Four of these 16 body segments make up *Manduca*'s thorax, which includes another six smaller legs [6]. Given the complexity of the caterpillar's muscular system, it is necessary to develop a simplified model to inform a worthy robotic design. Alluding to prior research showing that the thoracic legs make little contribution to the caterpillar's movement, *Saunders et al* chose to simplify their model by removing the thorax and focusing on the caterpillar's abdomen [6]. Their extensible-link model is shown in Figure 6.

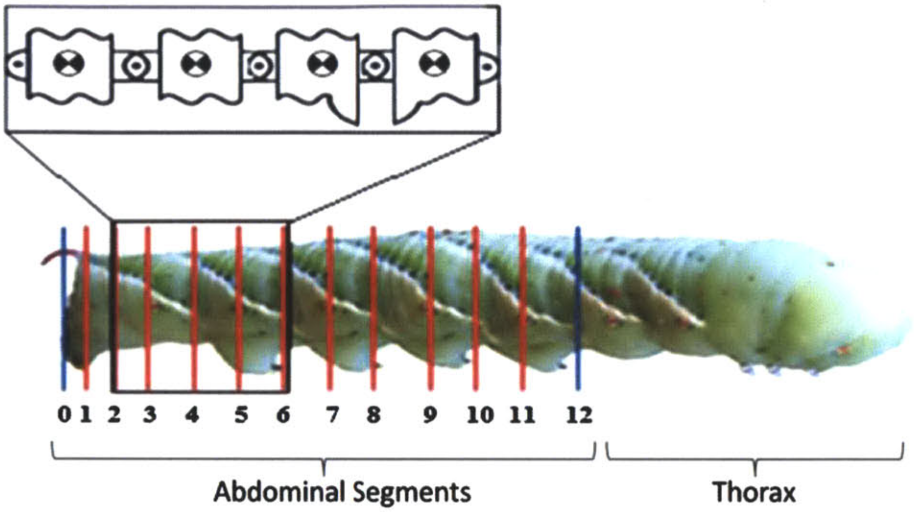


Figure 6: The extensible-link model of the *Manduca*, separated into 12 abdominal segments. [6]

To further simplify the model, the caterpillar's abdomen was reduced to twelve deformable links connected by revolute joints. In contrast to previous work applying continuum mechanics and finite element methods to describe invertebrate motion, this extensible-link model allows for fewer degrees of freedom, which allow internal and contact forces to be calculated using inverse dynamics. In inverse dynamics, the forces acting on each segment are calculated from measured accelerations [6]. The forces acting on a segment of the caterpillar are shown in Figure 7.

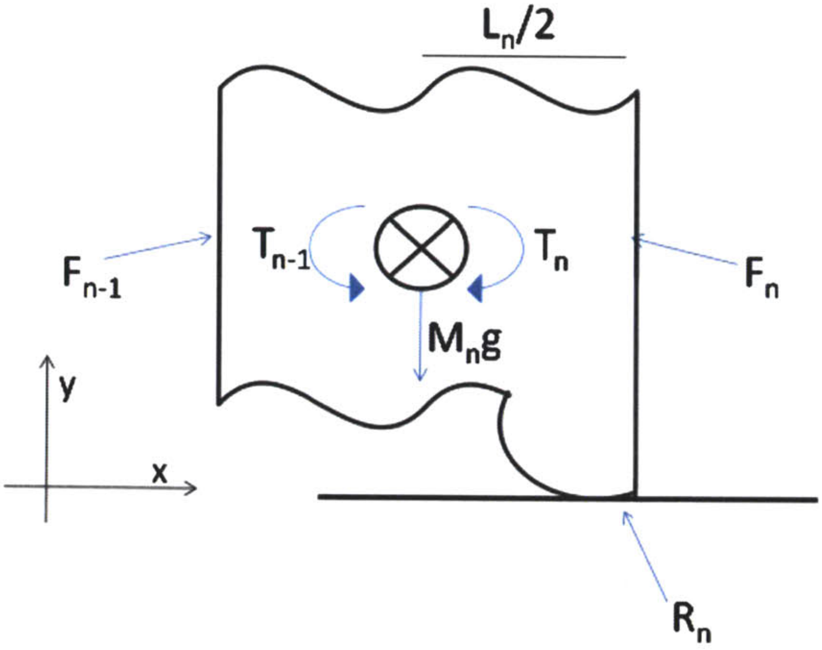


Figure 7: The forces acting on a segment of the modeled *Manduca* are shown in this free body diagram. [6]

This model's new analysis capability can be applied to study internal forces in caterpillar locomotion *in vivo*, which was not previously possible [6].

The modeling method developed in this research has helped to build a framework for how a caterpillar-like robot may be designed, providing key insights into how an arthropod moves, especially regarding weight distribution and shift of internal forces. The passive gripping of the *Manduca*'s prolegs provides the axial compression necessary for compliant links to be lifted off of the ground. Horizontal ground reaction forces were found to be as large as 5.3 times the caterpillar's body weight. Forces of this magnitude cannot be expected to be obtained through friction alone, given that typical friction forces are only a fraction of a contact point's normal force [6]. A caterpillar-inspired robot should be expected to utilize some form of gripping structures to provide for these high horizontal forces.

Further work is necessary in the design of motor control and robot structure, and how their interaction will affect the internal forces of robotic segments. Given its simplicity, this model can be easily refined for a given robotic application. Further study of the internal forces experienced in various caterpillar movements will inform expectations in performance capabilities of a bio-inspired caterpillar-like robot. By expanding the understanding of caterpillar locomotion and facilitating further research in such analysis, this work has progressed the development of a soft-bodied arthropod-inspired robot. By focusing on the modeling of a biological system, this research has made a valuable contribution to the field of biomimetics.

Pulsed-jet underwater propulsion – Robosquid

With improvements in fabrication at the sub-millimeter scale, the development of small underwater robotic vehicles is now mainly constrained by the challenge of propulsion for a vehicle in the centimeter to millimeter size. Such an object would face low operating Reynolds numbers, in the range of $Re \approx 1\text{-}100$. Through the study of biological marine propulsion, pulsed-jet propulsion is suggested as an effective method under these flow conditions [7]. This paper describes the testing of a scaled underwater pulsed-jet vehicle. Dimensional analysis is used to compare the experimental results to what could be expected for a small underwater robotic vehicle.

Traditional propulsion by steady jets is only effective at high Reynolds numbers where the flow's inertial effects greatly overpower any viscous effects. Fish-like swimming is effective at slightly lower Reynolds numbers, but due to the movement's dependency on inertial forces, it becomes ineffective below a Reynolds number of a few hundred. Spiral and flagellar propulsion is common at very low Reynolds numbers much less than 1, driven by viscous forces in the Stokes flow regime. In the Re range of one to a few hundred, there is no optimized human-made propulsive method [7]. However, current research suggests that pulsed-jet propulsion, used effectively by many animals including squid and jellyfish, would offer the necessary propulsion under this flow regime. Pulsed jet propulsion is characterized by vortex rings, which improve thrust by accelerating surrounding ambient fluid, creating overpressure at the exit plane of the nozzle [7].

Using a submersible pulsed-jet vehicle, named Robosquid for its bio-inspired propulsion, *Moslemi, A. and Paul Krueger* tested the efficiency of the pulsed-jet while varying the parameters of the jet pulses. A schematic of Robosquid is shown below in Figure 8.

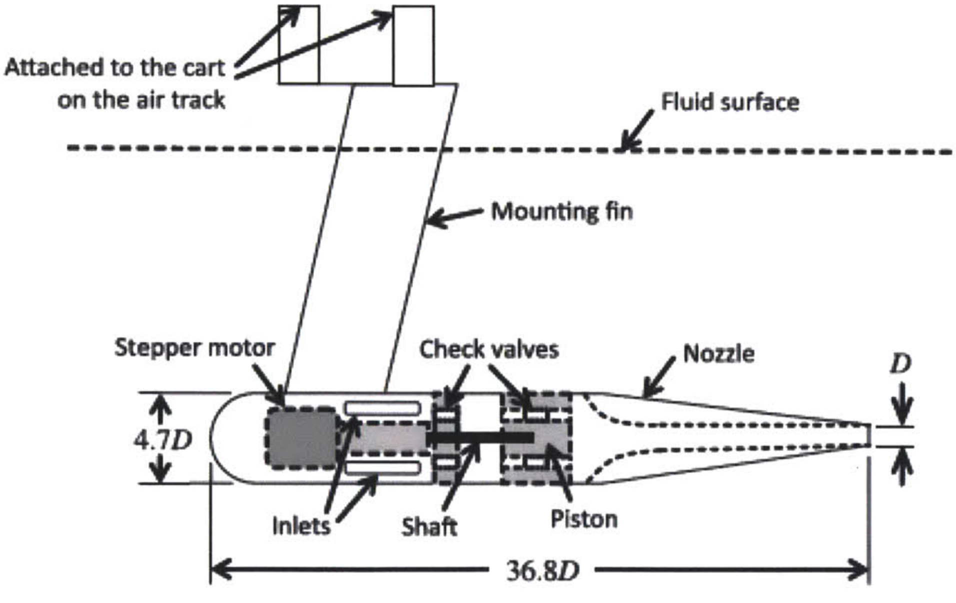


Figure 8: Schematic of the squid-inspired pulsed jet underwater vehicle, Robosquid. The diameter *D* of the nozzle is 1.91 cm. [7]

Dimensional analysis was used to determine the expected performance of a millimeter-scale underwater pulsed-jet robot in water, based on the Robosquid. A glycerin-water mixture was used instead of water to reduce the Reynolds number of the flow. Propulsive efficiency was analyzed while varying jet pulse parameters [7].

A critical dimensionless parameter is the jet slug length-to-diameter ratio, or stroke ratio, *L/D*, where *L* is the length of the expelled water jet and *D* is the nozzle diameter. The stroke ratio characterizes vortex ring formation. Above a critical value of *L/D*, the vortex ring will pinch off and leave a trailing jet of water, lowering the efficiency as less of the pulse contributes to the propulsive benefits of the vortex ring's flow [7].

Another important parameter is the dimensionless pulsing frequency St_L, defined in Eq. 2,

$$St_L \equiv \frac{fL}{\tilde{U}_j}, \tag{2}$$

where f is the frequency of jet pulses and $\tilde{U}_j$ is the jet speed averaged over the duration of the pulse. By varying only the rest time t_r between pulses, St_L can be varied while holding *L/D* constant [7].

By isolating these dimensionless parameters, it was found that propulsive efficiency increased with lower *L/D* and higher St_L. In comparison to a previous study in water with the same pulsed-jet underwater vehicle, larger vortices form under low *Re*, as shown in Figure 9 [7,8].

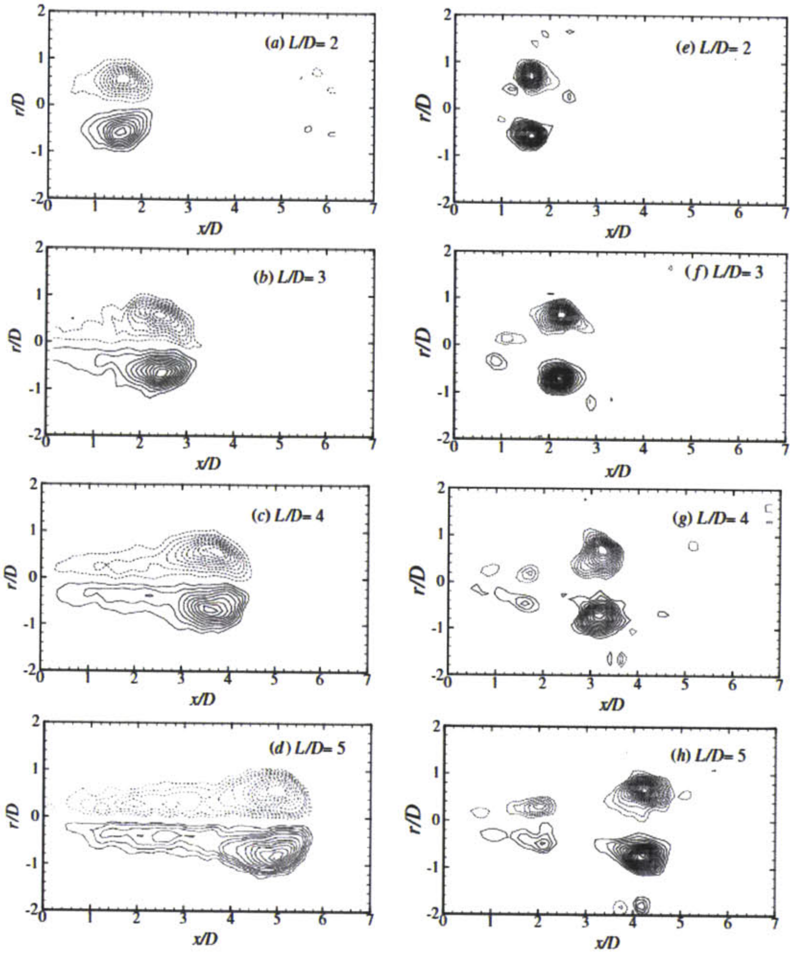


Figure 9: Vorticity contours of pulsed jets produced by Robosquid with St_L = 0.2 at (a-d) Re = 37 and (e-h) Re = 1300. [7,8]

Compared to the same study, the effect of L/D and St_L on propulsive efficiency in the two flow regimes can be seen in Figure 10.

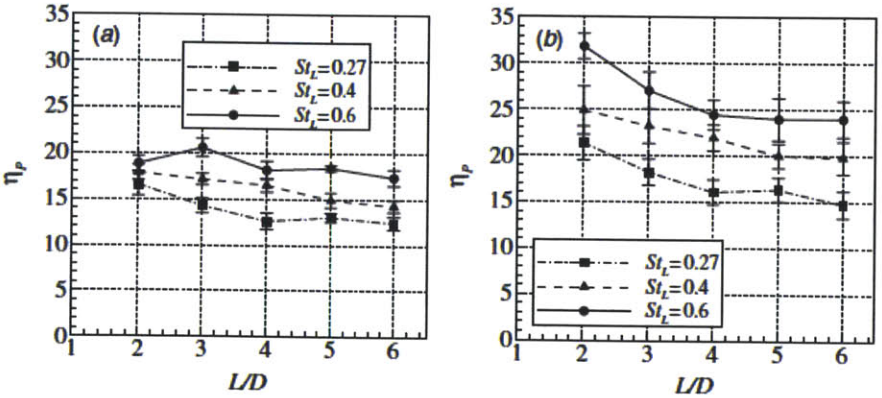


Figure 10: Propulsive efficiency as a function of L/D at varying St_L in (a) glycerin-water solution (Re = 37) and in (b) water (Re = 1300). [7,8]

While the overall propulsive efficiency decreased at lower *Re*, it was found that pulsed-jet propulsion loses propulsive efficiency at a slower rate than an equivalent steady jet, suggesting this mode of propulsion offers an efficient alternative in the range of *Re* = 1-100 [7].

It is clear that the researchers in this work performed an extensive literature review to better understand the propulsion methods of many biological organisms under various flow regimes. In the context of pulsed-jet propulsion, they noted a few mechanisms by which some organisms are able to further control these pulsed jets. This provides valuable insight into the design of their system, assuming it will be used in a similar or dimensionally similar environment as these organisms. Through experimental optimization of pulsed jets, this publication provides insight into how a pulsed jet vehicle may be effectively operated.

More can be learned from the biomimetic study of the sensing and control mechanisms used by squid and jellyfish, as well as their maneuvering styles. While the Robosquid has a structurally rigid body, the sea creatures that use pulsed jets are generally invertebrates with highly flexible body structures. Exploring this coupling may provide further insight into improving the efficiency of pulsed-jet propulsion as well as the agility of later pulsed-jet underwater vehicles.

Biomimetic Burrowing — RoboClam

The razor clam, *Ensis directus*, is easily able to outdig humans in search of a dining delicacy. It has mastered the act of burrowing. By fluidizing its surrounding substrate with shell movements, the bivalve is capable of digging to 70 cm at almost 1 cm/s while expending only 0.21 J/cm. This energy expenditure is the equivalent of traveling over half a kilometer on the energy in a AA battery, an order of magnitude improvement over current burrowing technology [9]. This paper describes the design and optimization of an efficient burrowing robot meant to inform subsea digging applications.

The razor clam is able to dig into the soil without any complex mechanisms. The shell has a single degree of freedom. By contracting, it is able to force blood into the clam's foot, which acts as an anchor as it drags the body of the clam downward. This movement is alternated with the foot pushing the shell up, loosening the surrounding substrate for subsequent burrowing [9]. A robot, called RoboClam, was developed to mimic the razor clam's burrowing technique, as shown in Figure 11.

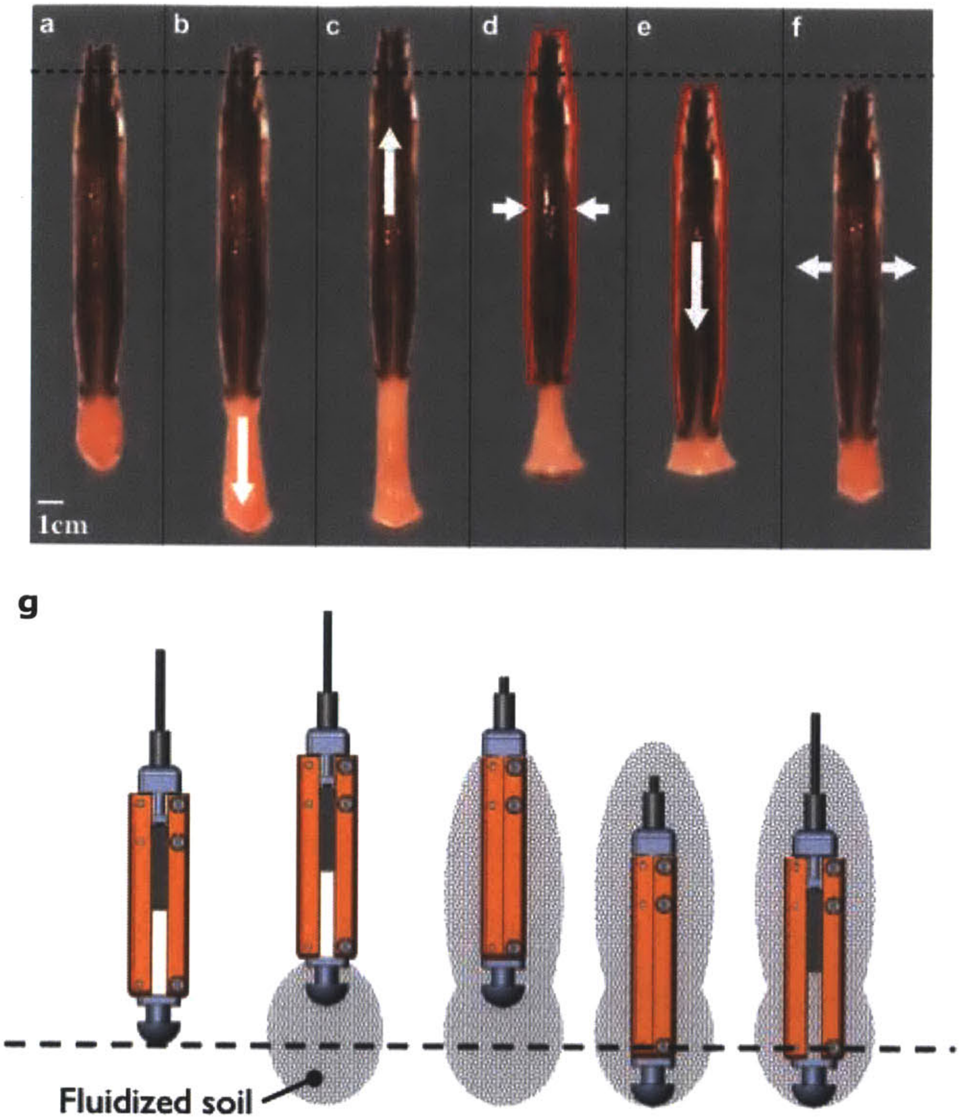


Figure 11: (a-f) Kinematics of clam burrowing. (g) Kinematics of RoboClam burrowing. [9]

RoboClam is actuated using a vertically sliding wedge to push the sides of the robot outward, and an inner rod to translate vertically [9].

RoboClam was tested under natural conditions in *Ensis'* marine habitat, while varying the parameters of RoboClam's actuation. The overall energy expenditure per depth of the robot, β, and the power law relationship, n, between depth and energy expended, were found to be the key factors to performance optimization. Aiming to keep n close to 1 and β as small as possible, RoboClam's performance was optimized by minimizing the product of β and n for the performance cost GA_{cost}, as shown in Eq. 3 [9].

$$GA_{cost} = \beta n \tag{3}$$

The development of the RoboClam is an ideal example of effective implementation of biomimetics. Throughout the process, it is clear that the value of nature's evolutionary design process was incorporated. The researchers' stated hypothesis was that "nature has found an optimized solution to subsea burrowing" [9]. By studying the razor clam, they were able to explain its efficient locomotion and to design a synthetic system inspired by the clam's burrowing mechanism.

Not only is the robot's design a great example of bio-inspiration, the optimization process used to determine efficient digging kinematics was inspired by genetic evolution. Using a genetic algorithm, the parameters of RoboClam's digging were varied through random mutation and recombination of traits, tending toward a globally optimal solution [9]. Through this method, the researchers were able to optimize their own engineering model *in situ* after obtaining the benefits of the razor clam's design. The performance improvement during experimentation in a mud flat in Gloucester, MA is shown in Figure 12.

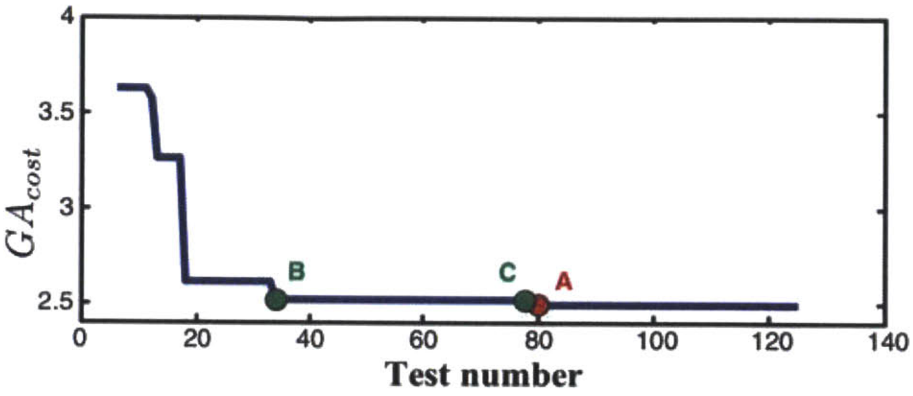


Figure 12: Optimization cost results from 125 trials performed in a mud flat in Gloucester, MA. Points A, B and C mark the lowest cost trials. [9]

The design process followed by *Winter et al* clearly recognizes the four critical elements of biomimetics research as outlined in this thesis. Focused biological research leads to a strong understanding of the burrowing kinematics and environment of the razor clam. By abstracting the functional components needed by the clam to burrow, a simple and effective robot is designed and subsequently optimized. Core engineering methodology is utilized and a synthetic specimen is presented with burrowing capabilities far surpassing any similar device. Intentional or not, this work is a great example of successfully applying the key steps of biomimetics.

Woodpecker-inspired Shock Absorber

Yoon & Park seek a novel shock absorber design, after studying the dampening capability of the woodpecker's skull [10]. The golden-fronted woodpecker, *Melanerpes aurifrons*, drums its head at a frequency of 18-22 Hz, experiencing a deceleration of 1200 *g*. For any regular verrtebrate, the forces experienced would immediately cause brain damage (concussion) and/or g-force induced loss of consciousness (G-LOC) [10]. By attempting to model the woodpecker's skull structures, the researchers suggest a simplified model of the skull's dampening components. They then design a shock absorber for the protection of commercial micromachined devices from high acceleration and high frequency mechanical excitations.

The researchers use x-ray CT scans to study the endoskeletal and tissue structures within the woodpecker's head. A large, elastic beak withstands high stresses from pecking. The hyoid, a musculotendinous tissue that attaches to the tongue and extends around the skull, allows for long tongue movement in catching insects and possibly bypassing mechanical vibrations. A spongy bone at the front of the skull is expected to dampen high frequency vibrations and prevent brain damage during drumming. And finally, a skull bone with a very thin layer of cerebrospinal fluid surrounds the bird's brain [10]. The woodpecker's skull structure is shown below in Figure 13.

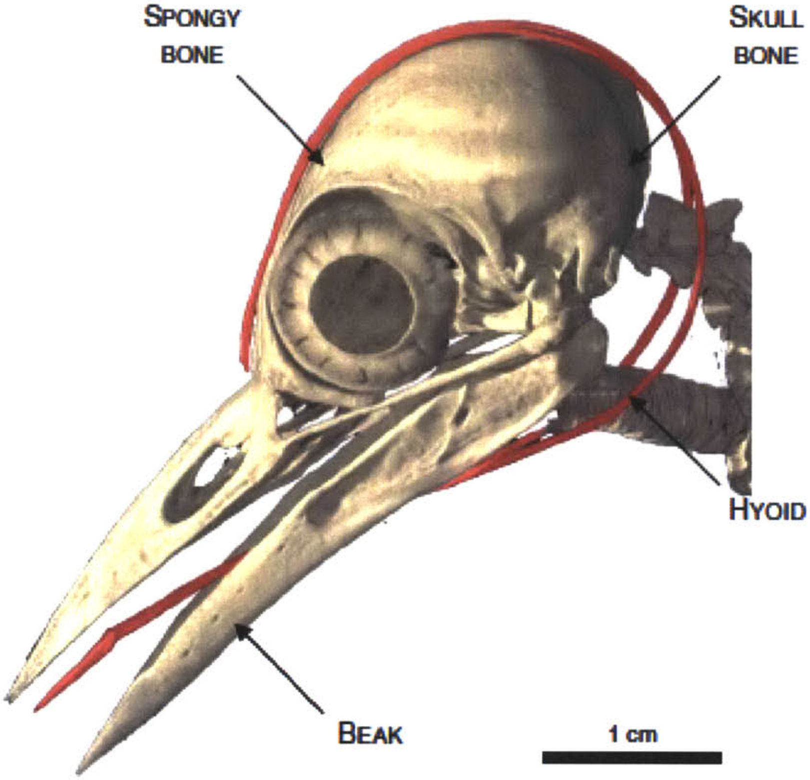


Figure 13: The skull of the *Melanerpes aurifrons* is composed of a large, elastic beak, the musculotendinous hyoid tissue (shown in red), the spongy bone, located just below the surface of the front of the skull, and the skull bone containing cerebrospinal fluid. [10]

Up to this point, extensive background research has provided valuable insight into the woodpecker's skull structure. It has led to the determination that the spongy bone is likely responsible for the dampening of deadly, high frequency, high g-force oscillations [10]. However, the modeling that follows is inconsistent to the skull's geometry and leaves the spongy bone indeterminate, providing equations and analysis that must be considered inaccurate in its representation of the head's dynamic behavior. The researchers' model of the woodpecker's head structure is shown in Figure 14.

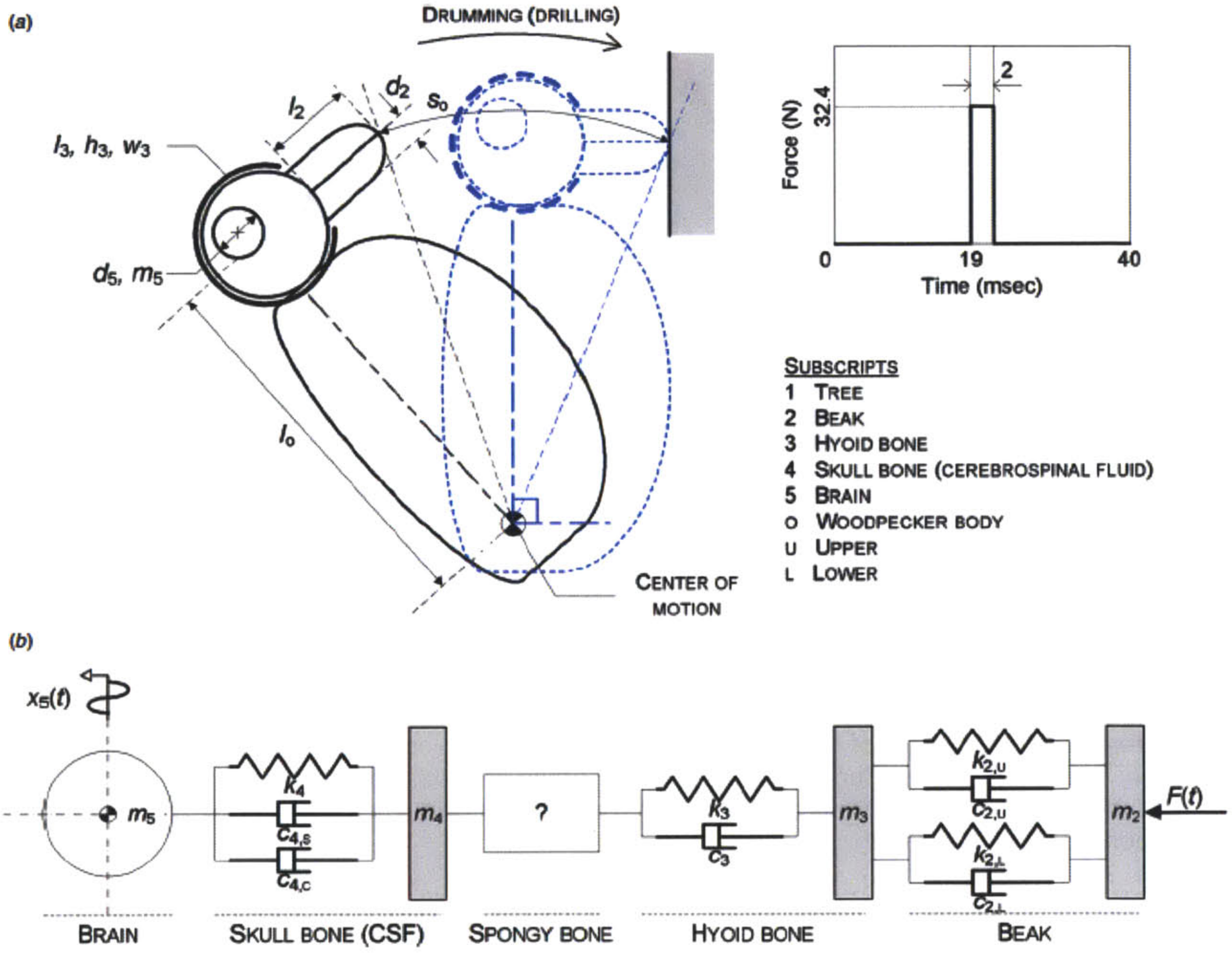


Figure 14: (a) Kinematic model of woodpecker during drumming. (b) Mass-damper-spring model of the woodpecker's skull structure. [10]

The mass-damper-spring model assumes that the head structure can be modeled as a linear series of structures, although the skull is not at all constructed in this way. From Figure 13, the beak appears to be rigidly attached to the skull bone, and it is not clear that it is actually joined to the hyoid. In the presented mass-damper-spring model, however, the beak is abstracted as attaching only to the two hyoid fibers through which it is attached in series to the spongy bone and then to the skull bone. With an object of mass *m*, damping coefficient *c* and stiffness *k*, the system is modeled using the equation of motion,

$$m\ddot{x} + c\dot{x} + kx = F(t), \tag{4}$$

at a displacement of *x* while experiencing an external force *F*. The researchers choose to remove the spongy bone from their model and assume it can be analyzed after characterizing the rest of the system, as shown in Figure 15.

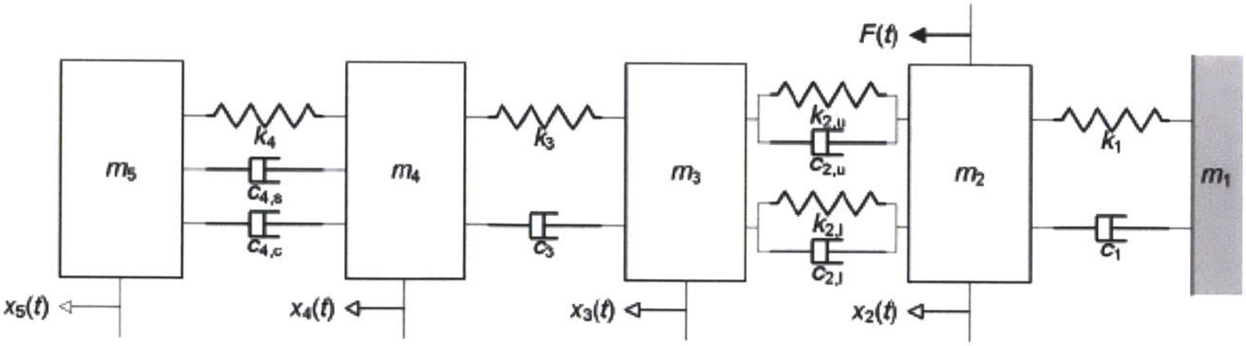


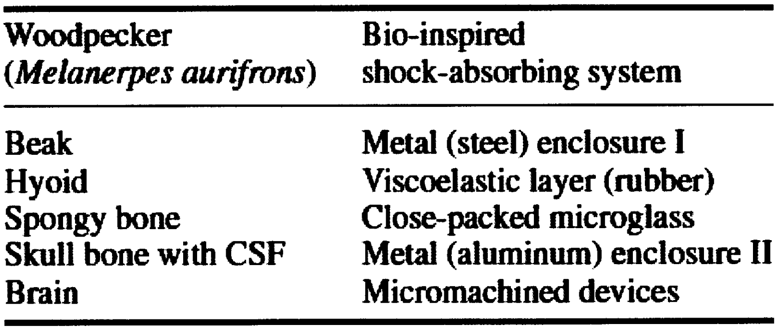
Figure 15: Mass-damper-spring model with spongy bone removed. [10]

While eliminating the unknown element from the model leads to a solveable system, the resulting model is not equivalent to the original and its solution should not be interpreted as the behavior of the actual system.

Yoon & Park continue by modeling the components of the woodpecker's head in order to calculate the brain's vibrations without the spongy bone as determined by their model [10]. The spongy bone is then empirically modeled as a confined space of closely-packed glass spheres, and varying sizes of spheres are tested to obtain the desired dampening qualities. It is not convincing that glass spheres truly mimic the spongy bone structure, as the researchers claim, but they are successful in dampening high frequency vibrations under testing.

A shock absorbing container for micromachined devices is designed based off the researchers' model, using equivalent subcomponents as shown in Table 1 [10].

Table 1: Analagous subsystems between woodpecker and bio-inspired shock-absorbing system [10]



Woodpecker (*Melanerpes aurifrons*)	Bio-inspired shock-absorbing system
Beak	Metal (steel) enclosure I
Hyoid	Viscoelastic layer (rubber)
Spongy bone	Close-packed microglass
Skull bone with CSF	Metal (aluminum) enclosure II
Brain	Micromachined devices

The shock absorber proved successful, reducing the device failure rate from 26.4% in a conventional hard-resin shock absorber container down to 0.7% in the biomimetic container under 60,000*g* loading [10].

While the modeling in this paper was questionable and not clearly representative of the *Melanerpes aurifrons* skull structure, effective engineering practice led to the development of a successful shock absorber. By understanding the function of each substructure, the researchers were able to design a device that achieved the same goals. If a more thoughtful analysis of the skull was performed, it is likely an even better design could be achieved. Ultimately, the woodpecker's incredible ability to withstand extremely high accelerations at high frequency without any detrimental effects has inspired these researchers to design a new and improved shock absorber.

Biomimetics of human movement

Through the analysis of robotic and prosthetic arms, this article challenges a standard assumption of motion control. By attempting to distinguish between functional and aesthetic attributes of biomimetics, a number of crucial questions are presented that provide an enlightening perspective. While its content focuses on optimizing synthetic arm movement, its motivations can be applied in the context of any nature-inspired engineering discipline looking to optimize its process and results.

Harris, C. separates biomimetics into two categories: functional and aesthetic [11]. Functional biomimetics demands careful understanding of the problem that nature has solved and its relation to a similar problem in the synthetic system. Aesthetic biomimetics imitates nature for its own sake, requiring no analytical rigor. Aesthetic biomimetics is valuable in certain scenarios, such as in human prosthetics. In performance-improvement engineering work, however, a conscious awareness of what you are mimicking, and why, is critical. To most effectively apply nature's solution to an engineering problem, you must truly understand the problem that nature is solving. With differing constraints, nature's solution may not actually offer the optimized solution for your problem [11].

Human movements are commonly characterized by smoothness. Many robotic movements have been designed to mimic this fluid, bell-shaped velocity profile. However, it is not obvious why such intentional movements have this smooth quality, and if its application in robotics is anything more than an example of aesthetic biomimetics. By focusing on point-to-point arm reaching movements, Harris explores nature's potential cost functions, comparing the minimum jerk model, the minimum torque change model and the minimum variance model [11].

The jerk of a moving object is the derivative of its acceleration. The minimum jerk model suggests that the ideal trajectory between two points will maximize smoothness by minimizing the square of the jerk of the object in motion [11]. This can be expressed through the minimization of the cost functional *MJ* in Eq. 4,

$$MJ = \int_0^T \left(\frac{d^3y}{dt^3}\right)^2 dt, \tag{5}$$

for a position function y(t) and movement duration T. A movement from the origin ($y(0) = 0$) to amplitude A ($y(T) = A$), with initial and final velocity and acceleration set to zero as boundary conditions, yields the standard minimum jerk trajectory [11].

Minimum jerk will create a smooth, symmetrical motion. If minimum jerk is applied in functional biomimetics, it must be under the assumption that nature is optimized to maximize smoothness and that maximizing smoothness is the goal in the synthetic system as well [11].

Given differences in actuation and noise produced by a robotic arm versus a human arm, the minimum jerk model does not seem ideal. Because proportional noise has been empirically observed in human isometric force generation, causing a speed-accuracy tradeoff as larger commands yield greater error, the minimum jerk model does not adequately fit arm movement for longer motions. Harris suggests the minimum variance model as a solution, which accounts for the existence of proportional noise [11]. Minimum variance can be expressed through the cost functional *MV,*

$$MV = \int_0^T f(t) u^2(t) dt, \tag{6a}$$

where

$$f(t) = \int_T^{T+F} p^2(t' - t) dt', \tag{6b}$$

$u(t)$ is the control input, and $p(t)$ is the impulse response function of the system [11]. This model minimizes movement for a time F after the movement when the system is meant to remain stationary in the final position. While the *MV* model offers a better fit for human arm movement, this still does not imply the same model is ideal for a robotic application [11].

Unless proportional noise is the dominant source of noise, the use of minimum variance or minimum jerk models cannot be considered functional biomimetics. A robot arm may experience constant or signal-independent additive Gaussian noise, which will not lead to a speed-accuracy tradeoff. This would imply that the optimized trajectory for a robot arm would most commonly be to minimize the duration of the movement, thus reducing time to accumulate variance. The ideal model would then be bang-bang control, where the motor is switched between its maximum and minimum limits [11]. Figure 16 illustrates the constraints of proportional and signal independent noise.

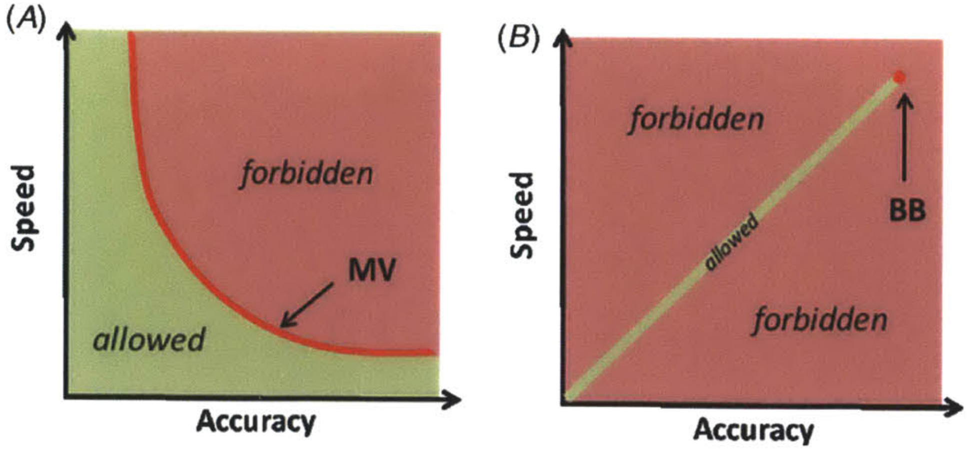


Figure 16: (a) Proportional noise forces a tradeoff between speed and accuracy, where minimum variance marks the highlighted ideal trajectory. (b) With constant or additive signal-independent noise, accuracy is a function of duration, and thus the ideal trajectory will utilize the maximum allowable speed. [11]

Harris seeks to emphasize the intent of functional biomimetics and the importance of questioning nature's design goals [11]. By realizing why the natural human arm movements fit a minimum variance model, we can see how a robot arm may have different constraints and function optimally under a different control model. "When we do not know the problem that nature is solving, we are essentially copying nature for its own sake—aesthetically." If the insight and depth of this study were applied to all biomimetics research, bio-inspired synthetic designs will have a greater chance of achieving optimal performance.

Robotic locomotion – the distributed foot

Professor Robert Full directs the Poly-PEDAL Laboratory at UC Berkeley, which studies the Performance, Energetics and Dynamics of Animal Locomotion in many-footed creatures. He gave a TED talk in 2005 describing his lab's research to better understand the foot [12]. By exploring many innovative mechanisms various creatures use to traverse challenging terrain, Full assembles an integrated model for what the functionality of a foot can encompass.

A mesh surface is used to simulate rough terrain, removing 99% of the contact area that would be present on a solid surface. By watching different animals cross the surface, Full found that grass spiders and cockroaches had no difficulty and were not slowed down at all [12]. The bugs were not deftly stepping directly on the wire as they ran, but in fact used their legs as feet during the traverse. Through the use of a high speed camera, it was discovered that directionally stiff spines on the creatures' legs allowed them to grip the surface when bringing the leg down and easily slip away when lifting the leg up. Similar synthetic spines were attached to the legs of a crab. When the crab had previously struggled to cross the mesh surface, it was now able to dart across at top speed [12].

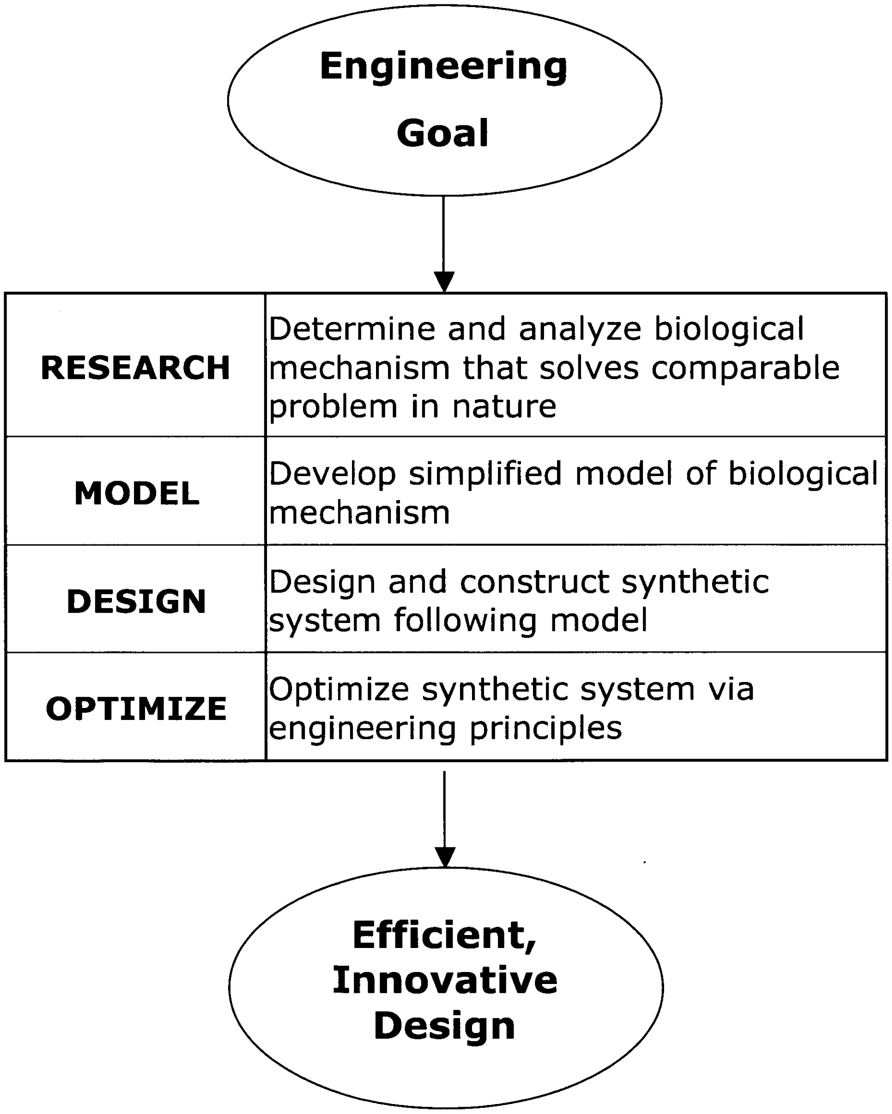
Different mechanisms are used to prevent slipping on surfaces of very low roughness. A certain species of ant passively extrudes a gluey pad from its foot as it steps on a smooth surface, providing traction. The high surface area of gecko's toes, made up of billions of 200 nm pads, use intermolecular Van der Waals forces to attach to very smooth surfaces [12].

By expanding the function of the foot to be distributed along the leg and utilizing many different mechanisms to overcome different terrain challenges, Full offers an integrated and robust model that holds the potential to outperform a natural foot [12].

Through this insightful research, Full offers a few key lessons in the study of biomimetics. First, control should be distributed amongst smart components. Integrating spines and microscopic split ends akin to the gecko's foot offer much greater value than an overly complex control system. And with the rapid prototyping process SDM, this approach is becoming more and more feasible. Second, it is critical to understand that nature uses hybrid solutions, which cultivate resilience in the face of variable challenges. And third, the goal of biomimetics is not to copy nature but to find inspiration and improve upon nature by combining novel principles with engineering solutions [12].

Methodology of Effective Biomimetic Design

Through the analysis of these works of biomimetic engineering, a methodology to achieve successful bio-inspired design results is suggested. This process is outlined below in Figure 17.



RESEARCH	Determine and analyze biological mechanism that solves comparable problem in nature
MODEL	Develop simplified model of biological mechanism
DESIGN	Design and construct synthetic system following model
OPTIMIZE	Optimize synthetic system via engineering principles

Figure 17: The biomimetic design process. Successful biomimetic design is dependent upon thoughtful research, modeling, design and engineering optimization.

The order need not be steadfast. The inspiration for an engineering problem may arise from the study of biology, or design iterations may demand a reassessment of the system model. What is critical is that no element is overlooked. For a synthetic system to most effectively incorporate a design solution found in nature into its own design, the natural system must be studied to determine the constraints that made it an advantageous trait. Only then can the essential components be extracted to construct the simplest functional model of that system. And, ultimately, the inspired synthetic system can be improved by applying engineering knowledge to optimize the final design beyond nature's capacity.

Most papers were very successful with one step in this process, while few excelled in all. In the development of a flexible wing micro air vehicle, the study of bird's wing movement was of great value and provided insight into the range of motion that a wing morphing aircraft might need [4]. However, the study of the wing under high maneuverability situations was not fully realized, preventing the development of a model that adequately accounted for wing shape in challenging maneuvers.

The soft-bodied arthropod work was only meant to fulfill one step in this process, constructing a model of caterpillar locomotion capable of calculating the body's internal forces [6]. It will be the responsibility of whoever uses this research to ensure that the model's assumptions align with their design constraints and to employ quality engineering.

The Robosquid, on the other hand, made little attempt to copy the biological structures of the squid beyond its cylindrical form, only showing close attention to its means of propulsion. If the squid or jellyfish's natural mechanisms used in propulsion were studied, a vehicle capable of greater maneuverability and efficiency could likely be developed. However, for the given focus of the study, valuable progress was made in offering validity to pulsed jets as a means of propulsion for small (mm to cm-scale) underwater vehicles.

The development of the RoboClam followed the presented process of biomimetic design, achieving an impressive underwater robotic burrowing system. This success was thanks to the researchers' well-orchestrated research, modeling, design and optimization processes, with the insights of nature at their disposal.

The woodpecker-inspired shock absorber, as described in analysis, was well researched and engineered, but the modeling of the woodpecker's skull was rather inaccurate. If the model were improved upon, insight into further optimization of the synthetic shock absorber could be possible.

The study of point-to-point movement was focused on the criticality of understanding an engineering objective. An important part of the biological research of biomimetics is to clarify all disparities between the constraints of the natural and synthetic systems [11]. While nature has optimized a limb movement to be smooth, this is because of how motor neurons and muscles are most efficient. Because this is generally not applicable for a motor-actuated system, the quality of smooth movement should not be a design specification [11].

Each paper's effective (+), ineffective (-) or nonexistent use of these four elements of the design process is shown in Table 2.

Table 2: Core biomimetic elements in reviewed literature. An assessment of if each research team successfully employed biological research, modeling, synthetic design and engineering optimization in their biomimetics research. An empty box implies that the associated method was not employed.

	Wing Morphing	Arthropod Model	Pulsed-jet RoboSquid	RoboClam	Woodpecker Shock Absorber	Human Movement
RESEARCH	+	+	+	+	+	+
MODEL	-	+	+	+	-	+
DESIGN	+		+	+	+	
OPTIMIZE				+		

Biological research is the cornerstone of biomimetics, without which an engineering project can clearly not be bio-inspired. In the literature reviewed in this thesis, there was a clear focus on seeking a deeper biological understanding across the board. In order to apply this knowledge in another context, namely robotic design, it is necessary to understand the biological system well enough to create an abstraction of the biological elements of interest.

Modeling was an integral component of the work in all of the articles read, however there were instances of insufficient or incorrect modeling. In these cases, however, the expected outcome is not failure to achieve a good quality final design, but certainly a less optimal design. Sound engineering is critical in the design and system optimization of synthetic mechanisms, and can also repair some of the damage of poor modeling.

Not all of these articles sought to produce synthetic systems at this time. Those that did are considered successful in their efforts by their quantified results and publication through peer-reviewed approval. The RoboClam was the only synthetic device that had undergone some amount of optimization at the time of publication. All of the research seeks to inform future engineering work and the design of bio-inspired synthetic systems, while some will lead directly to such efforts by the same research team.

Conclusion

Biomimetics has far-reaching applications with high potential for performance-improving innovation. Current research shows a variety of approaches to derive design inspiration from nature. While all of the work reviewed advanced the development of biomimetic design and the knowledge base of bio-inspired robotics, the research that most effectively applied nature's ingenuity was able to clearly articulate the constraints of the observed natural system. For a biological mechanism to offer valuable design inspiration, it must be similarly constrained and solve the same challenges as the designer's synthetic system.

Successful biomimetics requires four key elements: (1) a clear understanding of the natural system, gained through depth of biological study, (2) the development of a simplified model that encompasses the core elements of the natural system, (3) the design of a synthetic system that meets the model's specifications, and (4) engineering optimization to improve the final design.

Through thoughtful research, development of biological models and the design iteration of bio-inspired robots, biomimetics can drive new and exciting methods of efficient and robust robotic locomotion.

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