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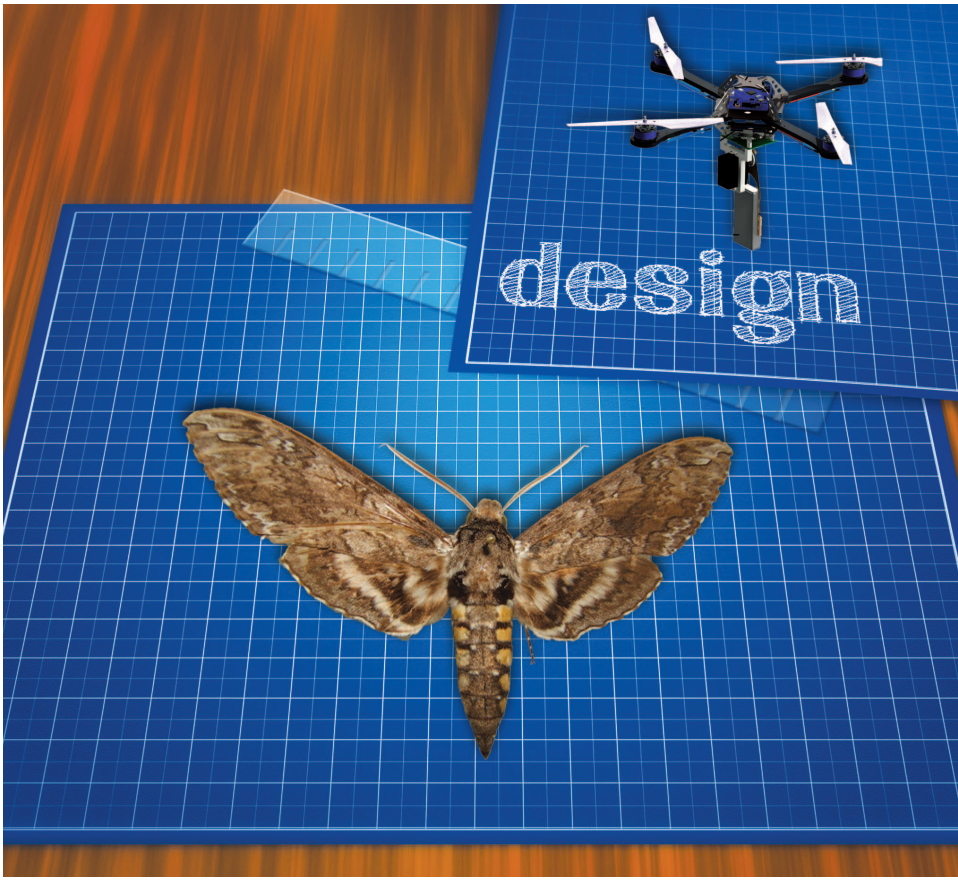
Mimicry or scrutiny? Striking a partnership between engineering design and biological research

Manu S. Madhav and Robert W. Nickl

The richness of the biological world is a testament to the diversity of life, the conditions under which it can endure, and the remarkable array of robust solutions to environmental challenges. Animals have, over millions of years, evolved complex computations to parse the richness of their natural sensory milieu, as well as mechanisms to transcribe this information into appropriate motor actions. For designers of mechanical systems and robotics, biology represents a vast library of possibilities and solutions. It is "natural," of course, to seek to imitate these solutions in terms of robotic systems trying to address similar challenges.

The capabilities of biological and mechanical systems are distinct, even when they are sensing the same stimuli and executing similar high-level tasks. Biological systems afford highly parallel computation and sensing, can adapt to unfamiliar environments, are able to regenerate and reproduce, and, in several cases, are able to act socially as well as individually. Mechanical systems can be stronger and tougher, provide sensory precision and range well beyond what is biologically plausible, and explore a wider design space (e.g., radar, commutation).



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The standard approach in biomimicry, arguably, is to *observe* a biological system or behavior, in either a natural or artificial setting; *design* mechanisms and algorithms to broadly imitate that behavior; and *synthesize* a realization of that design with available or manufacturable components. The book *Biomimicry for Optimization, Control, and Automation* argues: "We do not care if the neural, fuzzy, expert, planning, attentive, learning, or genetic systems model their biological counterparts—we are simply trying to get ideas from how they work to solve engineering problems.... In other words, we seek inspiration from biological systems, but when it is convenient we will not follow the

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functionalities or ideas that are suggested by biology." As a byproduct of this type of imitation, biology is often cited to justify certain engineering approaches or to highlight the possibility of human ingenuity to replicate nature.

"Biomimicry," often used synonymously with "bioinspiration," is a valid engineering approach, although in many cases naïve. We contend that a broadened approach to bioinspiration, driven by a deep mechanistic understanding gained by scientific study of the natural behavior of interest, is a path toward more informed and perhaps ultimately more fruitful design. This approach differs from biomimicry by the addition of a critical step: that of analysis prior to design, where a biological behavior or property is understood with respect to its environmental, evolutionary, and social context.

Formally, the analysis process often starts as the search to answer one or a series of specific questions. These may be purely biological: What prompts the behavior of interest? What is its social and developmental context? Does it play a functional role or is it an artifact of developmental, evolutionary, or other constraints? How did the behavior evolve? On the other hand, questions may be rooted in engineering: What are the nature and bandwidth of the stimuli received? What constraints do the actuators have? What computational algorithms drive the behavior? Still other questions can bridge engineering and biology: How do constraints on sensing and actuation influence the behavior? How much does the behavior depend on social versus individual influences? Could we tailor and reweight these influences in the design to suit our priorities?

Resultant knowledge from these analyses must be detailed enough to enable synthesis. Ideally, we should understand and quantify the behavior to such a degree that it would be possible to replicate the behavior, were we able to directly engineer an organism. Of course, abstractions and simplifications need to be made, but the important point is to understand not just how a biological solution is implemented, but its purpose, its context, and the conditions under which it is best suited.

Biological systems afford highly parallel computation and sensing, can adapt to unfamiliar environments, are able to regenerate and reproduce, and, in several cases, are able to act socially as well as individually.

A case in point is the Mexican tetra *Astyanax mexicanus*, a species of fish that lives in both shallow and deep underwater habitats and presents in two known conspecific forms. One form is found in both habitats, and a biologically inspired engineer may attempt to mimic its conspicuous eyes in a design, concluding that they confer an ability to see in both bright and dim light intensities. This seems a perfectly reasonable approach, until one realizes that the alternate form of *A. mexicanus*, which can be found in deeper underwater venues, has "malformed" vestigial eyes, lending it the alternate name of the "blind cavefish." In this case, the presence or absence of external eyes misdirects the engineer away from a more interesting biological feature of this species: the presence of a "pineal eye"—a light-sensitive area in the brain similar to the pineal gland in humans, that enables it to skillfully detect shadows (Yoshizawa and Jeffery, 2008).

In the expanded process of bioinspiration we discuss, observation of animal physiology and behavior serves as a guideline: a reference as opposed to a solution template. This process calls for novel experimental and analysis techniques to examine biological systems, as well as a deeper understanding of the environment and challenges we seek to address with the robotic system.

Toward an inventory for bioinspired design

At the Locomotion in Mechanical and Biological Systems (LIMBS) laboratory at Johns Hopkins University, we use carefully designed and controlled experiments coupled with techniques from control theory to analyze animal behavior. This research has already yielded a deeper understanding of many biological systems of interest. In many cases, insights have been implemented in the form of computational algorithms and mechanical design parameters in actual robots (Demir et al., 2012; Mongeau et al., 2013). In other cases, they have suggested design implications that are still being explored (Sefati et al, 2013; Ankarali et al., 2013). In the following sections, we highlight research performed by both our collaborators and us on several animal systems, which has not only expanded biological knowledge, but also uncovered principles that can be translated to engineering design.

Case study 1: Ribbon fin locomotion in fish

The weakly electric knifefish *Eigenmannia virescens* [Fig. 1(a)] inhabit freshwater environments of Central and South America. They "see" their environment using electricity produced by an organ in their tail that generates an oscillating electric field, which is detected and interpreted via sensors (little "voltmeters") distributed over the body surface. Their locomotor system involves a remarkable ribbon fin that extends over almost their entire body length. This ribbon fin produces mutually opposing, counterpropagating waves (one originating near the head, one from the tail) that meet near the middle of the body, as if half the wave is trying to make the fish swim forward, while the other half is trying to make the fish swim backward. Does this seemingly self-defeating strategy of producing counterpropagating waves that fight each other provide advantages over a more "sensible" strategy of just producing a wave in one direction? Moreover, why would these fish expend energy just to stand still?

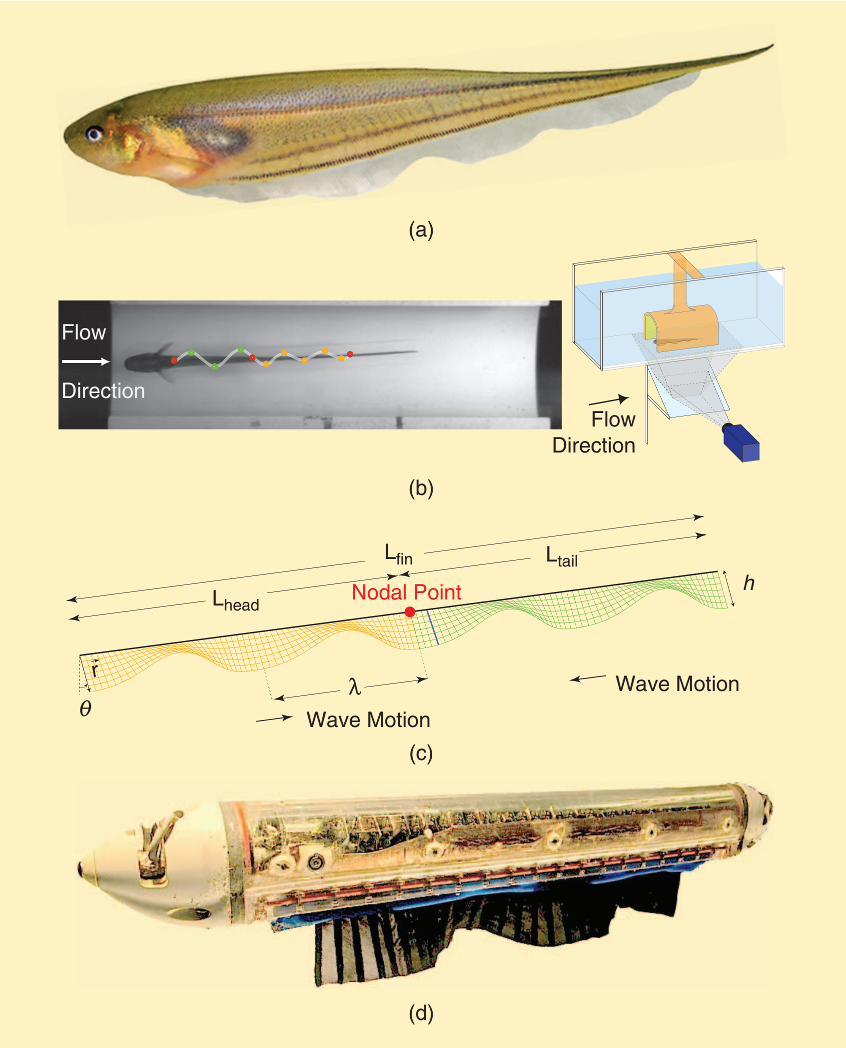


FIG1 (a) The weakly electric knifefish (*Eigenmannia virescens*). (b) The experimental setup using variable flow speeds to measure ribbon fin kinematics. (c) The visualization of a computational model that informed the linear force profile. (d) The ribbon fin robot (Northwestern University) that provided further experimental validation. (Adapted from Sefati, et al., 2013. Credit: Shahin Sefati and Izaak Neveln.)

Sefati et al. (2013) analyzed ribbon fin kinematics of fish swimming at different velocities [Fig. 1(b)]. Their data, coupled with a computational model [Fig. 1(c)], revealed a linear relationship between thrust and the difference in length between the head-to-tail wave and the tail-to-head wave. They validated this simple relation through force measurements from a robotic ribbon fin [Fig. 1(d)]. This is categorically different from the nonlinear force profile of a single traveling wave. The beauty of the linear relationship is that small adjustments to where the two waves meet—a simple and easy-to-control variable—provide an excellent means for maneuvering and control.

In addition, the group showed that when there is a perturbation to the animal, the wave opposing the perturbation automatically increases its force to counteract the perturbation, a passive mechanical effect that enhances stability. Thus, counterpropagating waves improve both passive stability and maneuverability. This is contrary to the popular design notion that stability and maneuverability must trade off of each other and shows that mutually opposing forces can enhance both simultaneously. Counterpropagating waves may also explain why, from an evolutionary point of view, this species has adopted the seemingly wasteful strategy of pushing against itself while hovering. It turns out this strategy is likely used by high-frequency flying animals like humming birds and insects (Hedrick et al., 2009). Thus, understanding the role of mutually opposing forces in these special cases can inform robotic design on multiple fronts.

Case study 2: Inertial stabilization in moths

The hawk moth, *Manduca sexta* [Fig. 2(a)] spends much of its life hovering and feeding in front of flowers. Dyhr et al. (2013) analyzed its stabilization techniques, particularly the visual-abdominal reflex. In a restrained experimental setup [Fig. 2(b)], moths moved their abdomen up and down in response to moving visual stimuli in the form of an oscillating horizontal bar pattern. Using a mathematical model of hovering flight, they demonstrated that movement of the abdomen sufficiently redirected the lift forces to stabilize flight.

Control and redirection of thrust and drag forces by controlling the shape of the airframe is a strategy that is underutilized in flying robots. Dyhr et al. used their hovering flight model along with experimental data to characterize a model of closed-loop visual-abdominal control. These principles were subsequently applied by Demir et al. (2012) to design a stabilizing controller for a quadcopter. For their design, Demir et al. emulated the abdominal mass of a hawk moth by mounting a battery unit to the quadrotor via a servo motor [Fig. 2(c)] and used feedback from pitch angle and rate (via measurements from onboard gyroscopes and an accelerometer) to adjust the "abdominal" angle between chassis and battery. Pitch perturbation experiments were conducted in which the robot was hit by a stick to knock it off balance while flying. By analyzing pitch angle, the researchers demonstrated that the controller was able to confer stability to counteract such perturbations. Making systems that are robust to perturbations (e.g., wind gusts) is essential for making effective robots.

Case study 3: Antennal sensing in cockroaches

The American cockroach, *Periplaneta americana*, [Fig. 3(a)] uses its antennae as versatile tactile sensors and rapidly navigates rough, unstructured terrain at an astounding rate, taking as low as 50 ms on average to execute a turn. Cowan et al. (2006) studied wall following in cockroaches by considering this behavior as a feedback control process in which measurements from the antenna are used to help the cockroach steer to avoid collisions with the wall. They found that the antenna-measured deviation from a preferred distance to the wall serves as an error signal, and the error as well as its rate of change are important cues for the cockroach mechanosensory system. Together these two signals measured by the antenna—position and its rate of change—inform a proportional-derivative (PD) controller (see “Proportional-Derivative Controllers”). Indeed, position and velocity are coded in the antennal nerve in a way that is temporally matched to the act of turning, not to the wall stimulus (Lee et al., 2008).

Following these behavioral studies, Demir et al. designed a robotic antenna comprising segments with tunable mechanical properties and equipped with hair-like structures like those found on cockroach antennae [Fig. 3(b)]. Based on this prototype and further behavioral experiments, Mongeau et al. (2013) observed that cockroach running speeds are invariant to wall surface smoothness. A characteristic of the cockroach's control strategy in both cases is the orientation of the front segments of the antenna: they are projected straightforward for very smooth walls but, more typically, they are curved backward near the tip for surfaces, which have some surface roughness. It turns out that the hairs on an antenna play a structural role by engaging with rough surfaces, thereby inducing a conformational change in the antenna; by curving backward, the antenna more smoothly follows along the wall, greatly facilitating control.

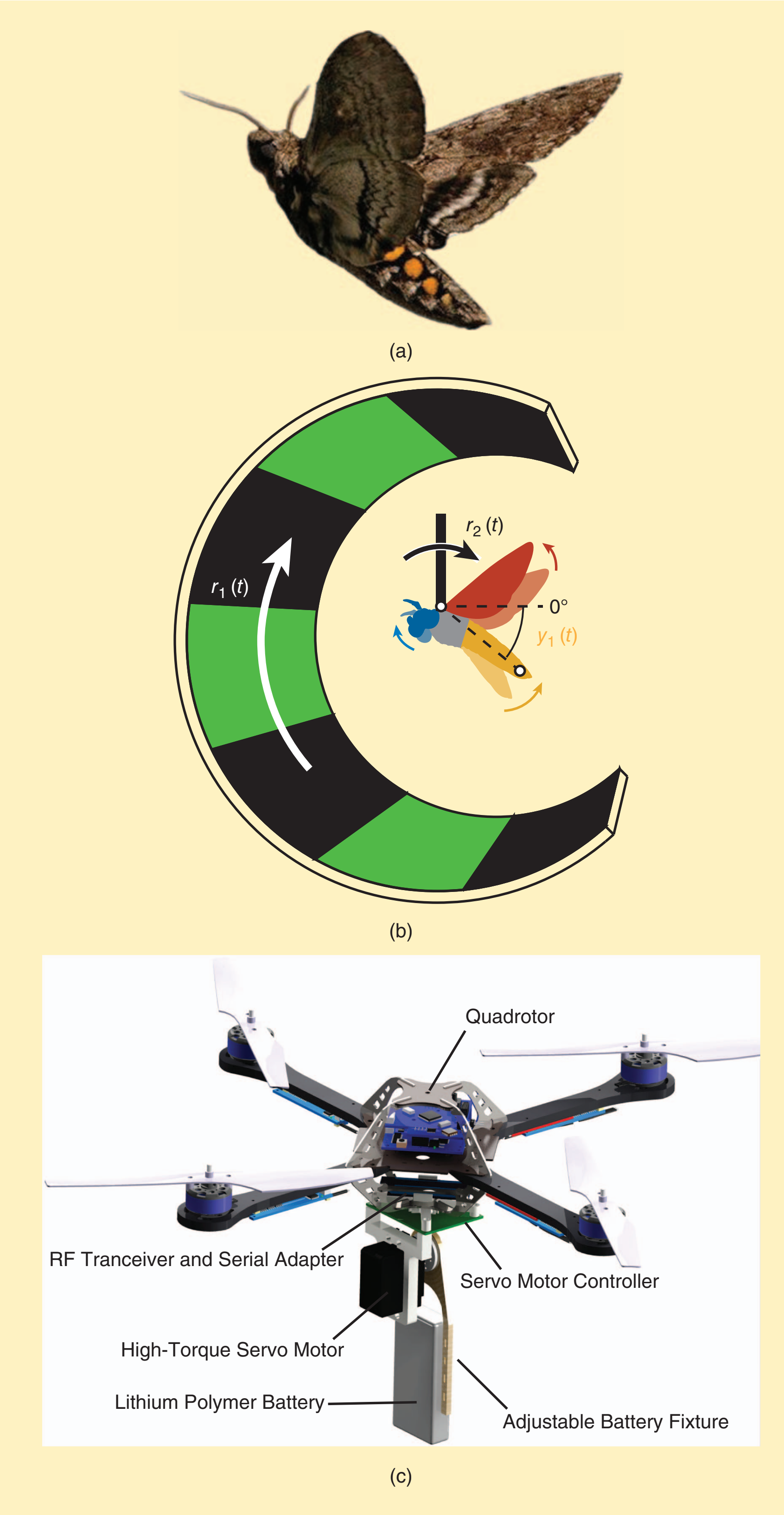


FIG2 (a) The hawk moth (*Manduca sexta*). (b) The closed-loop experiment to study visual scene stabilization behavior under restraint. (c) The hawk moth-inspired, self-stabilizing quadrotor. (Credit: Armin Hinterwirth, Jon Dyhr, and Alican Demir.)

Note that the engineering product, a robotic antenna, was used not as an end in and of itself; the

By studying these behaviors in a controlled environment, we strive to develop an understanding of these behavioral mechanisms that is sufficiently detailed to utilize in engineering designs.

researchers used this antenna as a physical model to enable a deeper analysis of the hypotheses regarding the biological system.

Case study 4: Neural sensing and stability in human rhythmic locomotion

The human, *Homo sapiens*, possesses an ability to walk upright that enables it to perform skillful tasks during locomotion. Legged systems can have great maneuverability and robustness—after all, humans (and many other animals) have no trouble stepping from smooth pavement to a gravelly footpath or simply hopping over a crack in the sidewalk. While examples of passively stable walking systems exist [McGeer, 1990], most bipedal legged locomotion involves a complex closed-loop interaction of limb dynamics and the neural controller. This combination of mechanical dynamics and control maintains robust, stable hybrid cyclic dynamics that are representative of most gaits. Several canonical models of bipedal locomotion (such as the spring-loaded inverted pendulum) have led to hypotheses that are testable against robotic or human walking data. While these models can sufficiently approximate the kinematics of walking, the nature of the underlying controllers and their interaction with the locomotor plant is poorly understood.

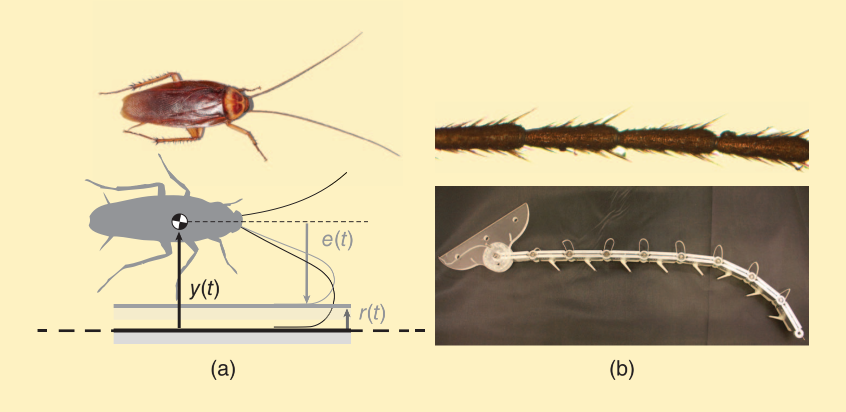


FIG3 (a) The American cockroach (*Periplaneta americana*) (top). Model of the cockroach's tracking error signal as distance from a wall (bottom). (b) Close-ups of cockroach antenna (top: note that hairs point distally, or away from antenna base), and cockroach-inspired antenna (bottom). (Adapted from Mongeau et al., 2013. Credit: Jean Mongeau and Alican Demir.)

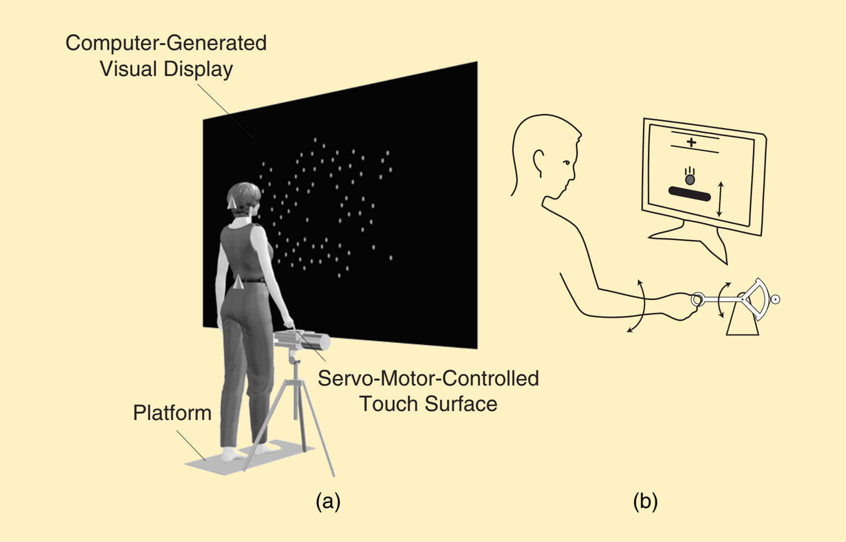


FIG4 (a) A human in a closed-loop experiment to measure roles of multisensory information to postural stability. (b) A paddle-juggling game to study dynamics of human rhythmic locomotion. (Credit: Kelvin Oie and Eatai Roth.)

Human-subject-based experiments led by engineers and biomechanists alike have shed light on the properties of these controllers. Typically, humans are placed in a closed-loop environment where conditions such as type and quality of sensory feedback are carefully controlled. To a volunteer participant, the experience is very much like playing a game. An experiment generally begins with a training phase when the volunteer learns the rules of the game and practices to achieve some baseline level of performance. As the experiment progresses, the researcher may alter the rules of sensory feedback or dynamics and observe the participants' responses. Cases when participants do not perceive these changes, but nevertheless adjust their behavior, are especially interesting. We highlight two such experimental settings that have generated insights into control of human locomotion.

To study human posture, Oie et al. (2002) performed a study where volunteers were asked to maintain a heel-to-toe stance on a platform while touching a surface and gazing at a projected dot pattern [Fig. 4(a)]. When the dot pattern and the touch surface were perturbed, the researchers found that subjects maintained postural stability by reweighting the influence of vision and touch information according to the perturbation amplitudes. Subsequently, these findings were used to design a controller to stabilize a bipedal robot with visual and vestibular information (Klein et al., 2011).

To study the cyclic dynamics of walking, Ankarali et al. (2014) created

Proportional-derivative controllers

In a wall-following task, if $y(t)$ is the position of the center of rotation of the cockroach at time t, and $r(t)$ is its desired distance from the wall, we can define the following error signal, $e(t)$:

$$e(t) = y(t) - r(t).$$

A proportional-derivative (PD) controller uses this error signal and its derivative $(de(t)/dt)$ to update the input $u(t)$ to the motor system (plant, P) that modulates the position:

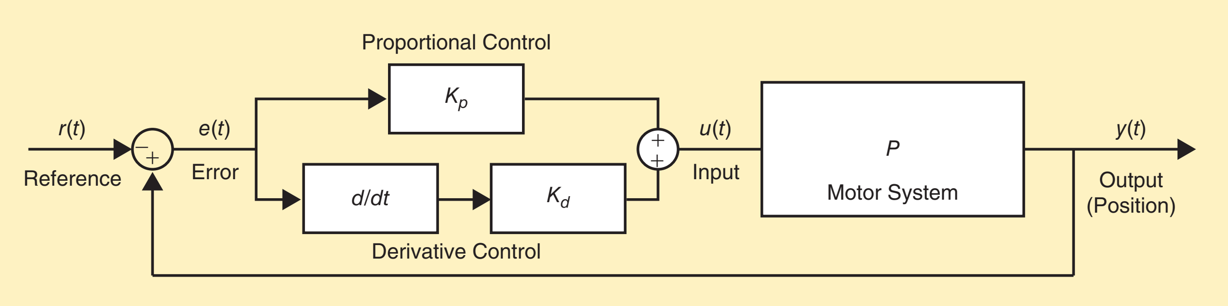
$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt},$$

where K_p and K_d are constant gains. To update the input, this controller accounts for the current error [proportional control, $K_p e(t)$], and the additional information of the error's direction of change [derivative control, $K_d(de(t)/dt)$] Thus, a PD controller would give the wall-follower an ability to anticipate future errors.

This suggests that the PD controller has the properties of a high-pass filter, which can be seen by its transfer function in the Laplace domain:

$$\frac{U(s)}{E(s)} = K_p\left(1 + \frac{K_d}{K_p}s\right).$$

A PD controller, with its high-pass filtering properties, suggests a plausible explanation for the American cockroach's ability to quickly process features of its environment via its antennae without the need for additional higher-order processing (Cowan et al., 2006; Cowan et al., 2014).



a virtual reality game, where human volunteers juggled a ball into a goal region with a haptic paddle [Fig. 4(b)]. This is a simpler task that nevertheless shares the hybrid dynamical structure of walking. As participants juggled, the saliency of the paddle-ball collision (the hybrid transition) was adjusted by switching tactile feedback on and off. By analyzing a subject's deviations around her average juggling pattern using linear systems theory, the researchers found that haptic feedback improved juggling accuracy with respect to the goal but did not affect how quickly a stable juggling pattern was reached. However, using concepts from terrestrial robotics, they demonstrated that haptic feedback does improve "metastability," i.e., the tendency of a person's cyclical movements to persist around a stable pattern.

Biomimicry is often driven by the desire to reproduce desirable high-level features or behaviors; however, mimicking low-level mechanisms does not always result in a product that is "optimal" by human conventions.

Biological analysis in the greater scheme of engineering design

A central thrust of our research is to identify biological organisms that perform certain complex behaviors exquisitely well and to quantify the algorithms and mechanisms underlying these capabilities through carefully controlled experiments subject to critical analysis with engineering techniques. By studying these behaviors in a controlled environment, we strive to develop an understanding of these behavioral mechanisms that is sufficiently detailed to utilize in engineering designs.

Often, these behavioral studies not only increase our scientific knowledge but also indicate new engineering design possibilities. The ribbon fin of the electric knifefish suggests that maneuverability can be improved without compromising stability. The hawk moth shows the possibility of improving flight stability by inertial manipulation of airframes. Wall following of the cockroach demonstrates how transducers such as antennae can be used both for environmental sensing and as a mechanical switch to facilitate control strategies. Human posture and rhythmic locomotion illustrate how adaptive reweighting of sensory signals can enhance stability and how information about hybrid transitions can promote metastability around walking rhythms.

Much of traditional engineering design, we posit, stresses what can be considered a top-down approach. Under this scenario, an engineering product is conceived in terms of its higher-order purpose (such as for a customer or end user), and designs

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are constructed that are deemed best to satisfy guiding criteria according to current knowledge and practices. In contrast, bioinspiration calls for a convergence between top-down and bottom-up approaches. To fully determine how a biological solution addresses task-level challenges, it is vital to examine the constraints and roles of its components (bottom-up) as well as their interaction to form the system-level topology (top-down).

Biomimicry is often driven by the desire to reproduce desirable high-level features or behaviors; however, mimicking low-level mechanisms does not always result in a product that is "optimal" by human conventions. This is not because evolution is a poor search algorithm: biological solutions are the product of a long series of refinements that have taken place throughout millions of years over an inconceivably large search space and have been tested over an amazing breadth of proving grounds. Rather, the criteria, if any, that evolution optimizes are often widely different from what humans may expect in a mechanical system. Complicating matters, the designs provided by evolution are constrained by history, development, materials, and fitness landscapes that change from generation to generation. Natural selection favors propagation of features that promote a species' overall fitness, such as number of surviving offspring (see, e.g., Burt, 2000), not whether that species was able to accomplish a specific task of interest to an engineer.

Humans are often predisposed toward certain concepts of what a "good" design is, which are informed by our personal experiences or by theories developed under assumptions. Bioinspiration challenges these canonical notions, and entails a different kind of objectivity in order to understand why (and indeed *if*) a particular natural solution works well for the animal or animals in which it evolved. A bio-inspired approach to design that is propelled by scientific experiments does not compromise traditional notions of design optimality, but rather gives the engineer an additional path by which knowledge can be validated, enhanced, and harnessed to develop novel or improved engineering products.

Read more about it

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