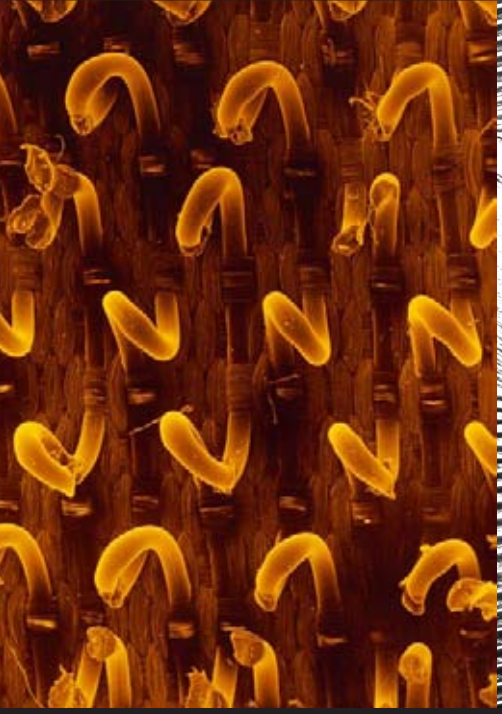
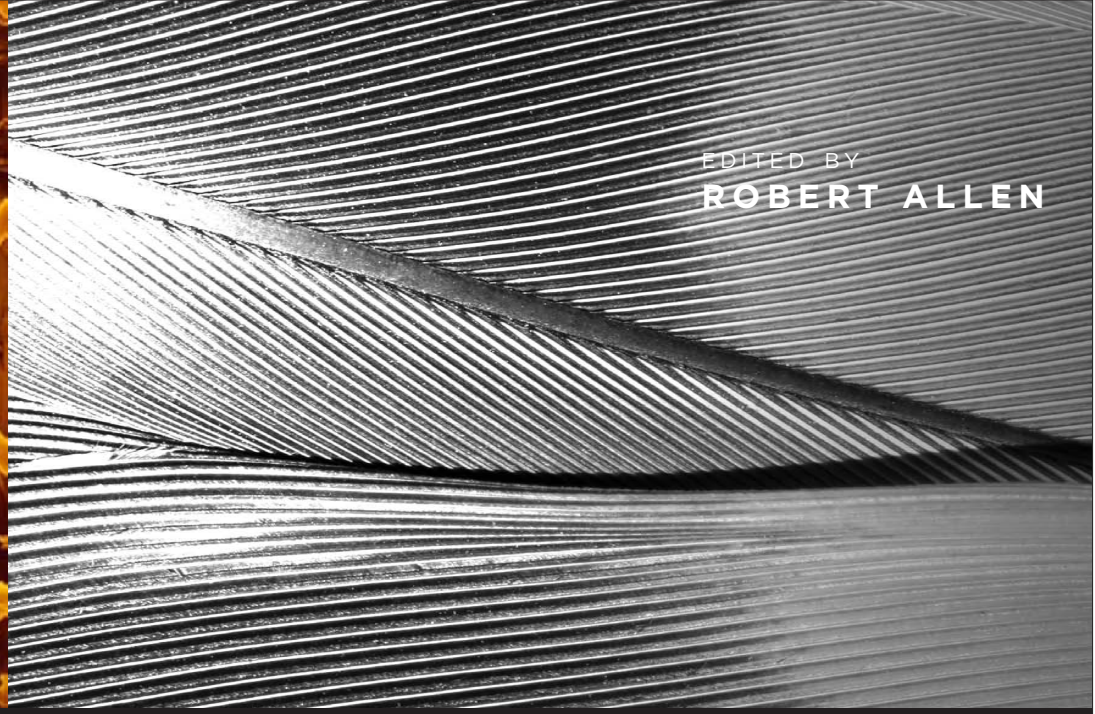




EDITED BY
ROBERT ALLEN

BULLETPROOF FEATHERS

How Science Uses Nature's Secrets to Design Cutting-Edge Technology

INTRODUCTION

WHAT IS BIOMIMETICS?

Who would have thought of flying had not birds shown the way; or of nylon without the spider or the silkworm? Wood is still more widely used as a structural material than all other materials put together. Horn, bone, and sinew have been used since the earliest times; we use plant fibres for making cloth and paper.

It is only within the last 30 years or so, however, that we have understood why and how these structures, materials and processes work. The discipline of biomimetics, or bio inspiration, is young and is itself an inspired union of biology and engineering. The invention of electron microscopes and our ability to see into the nano realm (a world of particles a millionth time smaller than an atom) have made it possible for us to begin to understand (and steal) nature's engineering and design secrets, even though we do not always get it right. This is not nanotechnology: biomimetics does not always build on such a tiny scale; it is enhanced observation and deducution, getting up close enough to see just how a natural solution to a problem or challenge has been arrived at, and endeavouring to replicate it. Many of the underlying ideas and clues have been available for some years, but we are only just starting to develop the techniques needed to realise their practical value.

This is a lot for non-sceintists to take in, and Bulletproof Feathers has been conceived and designed as a kind of primer in this fascinating subject. It starts with a review of early biomimics, including Leonardo, to show how the idea of letting nature's solutions answer some of our challenges, if not the ability to replicate the solutions, has been around a long time.

The main part of the book is divided into three sections: Borrowing Materials, Stealing Structures and Copying Processes. Borrowing Materials looks at how a huge number of natural materials are made with relatively few

basic building blocks (sugar, water, calcium, for example) and how we can copy these materials, either using the original recipe or replacing with synthetics, to achieve the same result. Materials examined include wood, spider silk, cereal starch. Stealing Structures looks at how holes and fractures can be used to for strength and protection. the way feathers development of a tough Structures examined include feathers, bone and nacre. Copying Processes looks at the way movement, action, growth and deployment makes a natural object behave. Processes examined include worm locomotion, self-cleaning leaves and wing deployment. In each case we look at the inspiration, find out how it works and then see how it can be applied to everyday life - for example, who would have thought that and unfurling leaf could inspire a warehouse storage solution?

Biomimetics, established barely 30 years ago, is a very young science, and there is much to discover. The final section of the book looks at inspirations and applications from nature that we can expect to see in the bnext 20 years or so.

Above Locust ears are located on each side of the insect's abdomen. The locust eardrum varies in thickness and so can function as a frequency analyser. The locust ear design is now being examined as a basis for the design of sensitive hearing aids that allow wearers to differentiate better between received sounds.

Left The gecko's foot is covered with ridges, which are lined with tiny hairs, which are themselves lined with microscopic hairs. These generate a subatomic force, the van der Wals force, which allows the gecko to stroll across ceilings and cross walls with falling off.

HUMANLIKE ROBOTS

Introduction

Over billions of years of evolution, nature has been making trial-and-error experiments within what we think of as the laws of physics, chemistry, material science, and engineering. The resulting outcome of these experiments is the wealth of fascinating creatures on Earth—including us, the human species.

HUMANS HAVE ALWAYS ENDEAVORED TO MIMIC and adapt human appearance, capabilities, and intelligence in both art and technology. The field of biomimetics is the latest expression of this endeavor, and the desire to engineer machines that display the appearance and behavior of biological humans, and that can perform various functions as efficiently as humans can, represents one of its biggest challenges.

Advances in computer technology, synthetic materials, artificial intelligence, real-time imaging, and speech recognition mean that it is becoming increasingly possible to create lifelike robots that closely resemble humans. Robots that verbally and facially express emotions and respond emotionally are being developed with impressive capabilities and sophistication. Electro-active polymers (EAP), also known as artificial muscles, are showing promise in enabling the development of biologically inspired mechanisms that once were considered possible only in the realm of science fiction.

This chapter looks at some of the earliest robots that resembled humans and where the inspiration for them came from, and then focuses on the state of the art today, the distinctive styles of robot, the challenges ahead, the potential impact of humanlike robots on our society, and the ethical concerns associated with the development and use of robots that are like humans. In order to do this, we will be using two terms to describe two distinctive styles of robot: humanlike robots and humanoids.

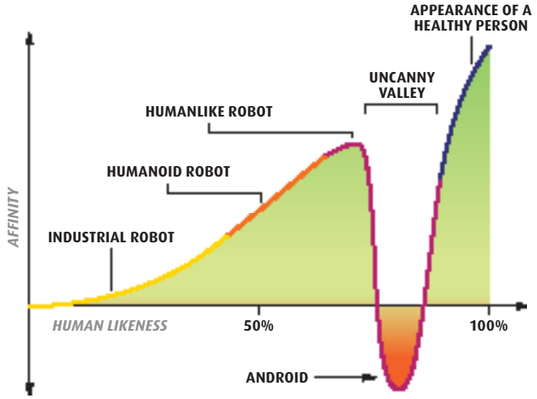
▲ Which one is the robot? The Chinese roboticist Zou Renti is on the left and his clone robot is on the right. This humanlike robot is one of the best attempts at making a copy of the appearance of a human but it is far from representative of the most sophisticated robots around today.

HUMANLIKE ROBOTS

These robots are designed to resemble a human as closely as possible. Great efforts are made to copy the exact appearance and behavior of humans. The roboticists making such robots are mostly from Japan, Korea, and China, with a few in the USA. An example of a humanlike robot is shown opposite.

HUMANOIDS

Humanoids are robots with a general human appearance that includes a head, arms, and possibly legs and eyes. However, they are clearly machines, and the head is often featureless or shaped like a helmet. Making humanoid robots is easier for roboticists because they are not required to deal with the complexities of completely humanlike machines.



▲ According to roboticist Masahiro Mori, public acceptance of humanlike robots will dip some time after they start to appear human, but it will be regained when the similarity becomes very close.

FEAR AND LOATHING

It is anticipated that improvements in the capability and applicability of humanlike robots will lead to their use as industrial and household appliances. However, humanlike machines may invite fear and dislike. In what is known as the Uncanny Valley, the Japanese roboticist Masahiro Mori hypothesizes that as the degree of similarity between robots and humans increases there will be an initially enthusiastic human response. However, when this similarity becomes very close, it will engender strong rejection and dislike. Only once the similarity reaches a very high level will the response become positive again. The negative feeling is graphically described as a "valley" in measuring the response to humanlike robots. The Uncanny Valley has its critics, who suggest that it has never been proven in a credible experiment.

◀ An example of a humanoid robot. While it has a broadly human appearance, with a head, torso, arms, and legs, its features appear more like a machine. This robot is called the REEM_A and it is made by Pal Robotics in Spain.

The Need for Humanlike Robots

Robots are entering our lives in education, healthcare, entertainment, domestic assistance, and military applications. Currently, entertainment robots are the most prevalent, with humanlike robotic toys widely available. One example is the Zeno interactive learning companion, a kind of synthetic pal.

THE MOVIE INDUSTRY HAS BEGUN to collaborate with scientists to make robotic characters appear more realistic and to move more like people. Robotics researchers are increasingly collaborating with artists to make their robots appear more expressive, believable, and heartwarming. The more we develop and interact with humanlike robots, the more sophisticated and lifelike they are becoming; and in the process, the greater understanding we are gaining of ourselves—scientifically, socially, and ethically.

▶ Zeno is a robotic friend and learning companion for children. He can link up to a computer, walk, talk, and recognize who you are. His soft face also shows emotions.

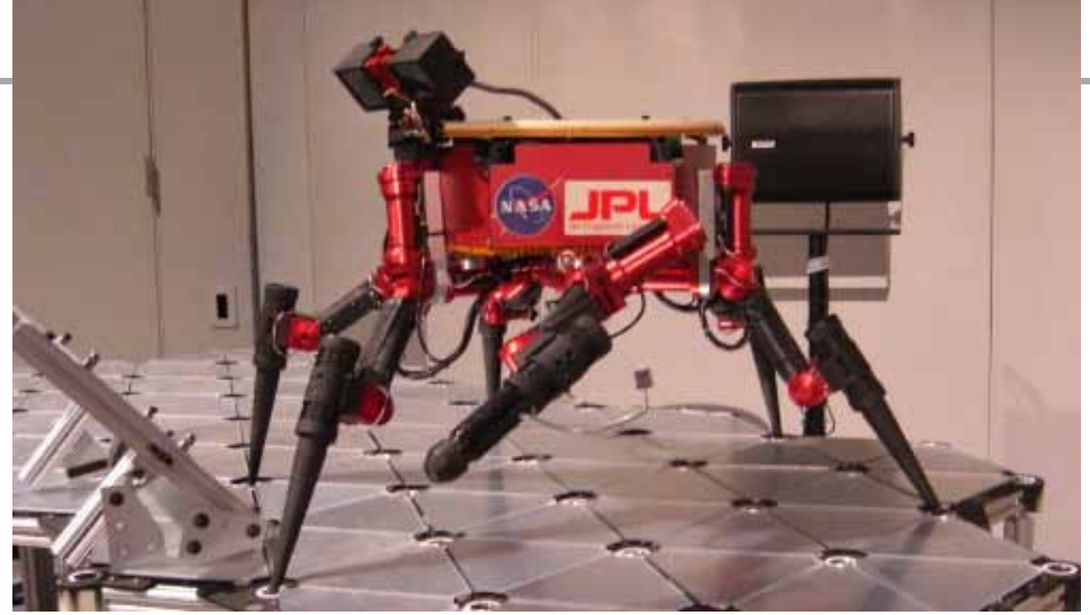
WHERE PEOPLE CANNOT GO

In industry, robot applications include planetary or deep ocean exploration and can operate in areas that humans cannot reach, such as places with toxic gases, radioactivity, dangerous chemicals, bad odors, biological hazards, or extreme temperatures. Within these areas robots could be used for clearing hazardous waste, explosives disposal, and search and rescue operations.

To be able to operate autonomously in these environments, a robot needs to perceive its environment, make decisions, and perform complex tasks independently just like a person would. Advances in this area have been enormous in recent years.

BEING HUMAN

The world we have built around us has been made to fit our body size, shape, and capabilities. This includes our home, workplace, and facilities, the tools we use, and the height at which we keep various items. Therefore, the robots that are being made to help us would best operate if they match our shape, average size, and capability. Such configuration will allow robots to reach handles to open doors, listen to us at eye level, climb stairs, sit on our chairs, drive our car, and perform many other support tasks for us. Also, since we respond intuitively to body language and gestures, it is highly desirable for robots to use facial and body expressions.



▲ This multi-legged robot is designed to traverse complex terrain. It was developed in the Jet Propulsion Laboratory.

WALKING LIKE A HUMAN

This humanoid robot, called Chroino, is made of carbon and plastic, which gives it a light but strong structure called a "monocoque frame". It was made by developer Tomotaka Takahashi at the Robo Garage in Kyoto University, Japan. The word "Chroino" comes from the words "to chronicle" and "black," the latter of which is pronounced *kuroi* in Japanese. Here are some of its key features:

❶ Incorporates new "SHIN-Walk" technology, enabling it to walk in more natural way almost as smoothly as a human does.

❷ Lightweight: it weighs just 2⅓ lb (1.05 kg).

GETTING AROUND

Constructing a robot that looks and behaves like a human is only one level of the complexity of this challenge. Making robots that can physically function within and outside our homes will involve the need to have them successfully navigate complex terrains. This involves dealing with static objects, such as stairs and furniture, and responding to dynamic ones such as people, pets, or automobiles. Tasks such as walking in a crowded street, crossing a street with traffic while obeying pedestrian laws, or walking in a complex terrain with unpaved roads require the determining of an available path that is safe and within the robot's capability. Technology to achieve this is the subject of research at many robotic laboratories worldwide.

Making Waves in the Water

Long before human beings used sounds to "see" invisible targets, dolphins and porpoises depended on ultrasonic pulse sounds to catch prey in murky waters or in darkness. Engineers are trying to understand how these work so they can develop new echo sounders that use sound to detect shapes and locations of objects.

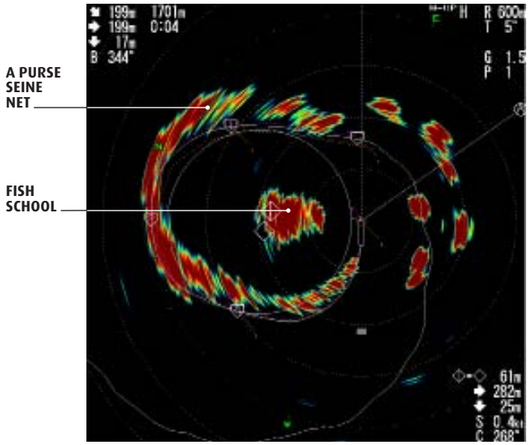
THE CHINESE RIVER DOLPHIN, OR BAIJI, can see nothing farther than 20 inches (50 cm) away in the muddy yellow water of the Yangtze River. To cope with this lack of visibility, the river dolphin uses ultrasonic sounds to sense prey and obstacles. The baiji and other toothed whales produce high-frequency sounds and listen for echoes to spot their prey. It was natural for toothed whales such as dolphins and porpoises to evolve this biosonar ability because they pursue each prey and catch it, one at a time, in the mouth. With biosonar, they can determine distance, size, material composition, and even shape and internal structure of underwater objects and distinguish between them.

SOUNDING OUT THE SURROUNDINGS

Humans have spent a lot of effort developing ways to identify targets under the surface of the water. Underwater poachers or secret agents with diving gear are very difficult to detect. A sensing system that could detect an unauthorized diver in restricted fishing areas or near an atomic power plant would be a valuable security measure. It would also help fishermen to locate the fish and ascertain what species they are before letting down their nets. The price of fish strongly depends on the species and size. Unfortunately, radio waves and light are not very effective for this because they do not travel long distances in water. With the naked eye we can see an airplane in the sky several miles away, but beneath the surface of the ocean we cannot see a submarine only 165 feet (50 m) away. Light is not effective for long-distance underwater sensing, but acoustics (or sound) is. Sound travels almost five times faster in water than it does in air and is less attenuated while traveling. This is why dolphins and porpoises use acoustic sensory systems for quick and long-distance searching in the water. Their most important target is fish; their sonar probably evolved to find and classify target fish suitable to eat. We can learn from dolphins' sophisticated biosonar systems as we develop echo sounders for fisheries to locate and identify shoals of fish.

◀ The wonderful sonar ability of the dolphin could help scientists develop an underwater sensing system that could detect poaching divers and other unwelcome intruders.

▲ The Chinese river dolphin (*Lipotes vexillifer*) has very small eyeballs with atrophied crystalline lenses and is unable to see visual images clearly so it uses ultrasonic sounds to locate prey and obstacles.



▶ A scanning sonar image of a fish school, which is about to be caught by a seine net. Sound is an effective tool to help visualize underwater targets, which is why dolphins and humans use it.

UNDERWATER BIO ACOUSTICS

Toward Dolphin-Mimetic Sonar

Major differences between dolphin sonar and conventional fisheries echo sounders are the broadband frequency characteristics and high spatial resolution of the former. Engineers and scientists are currently trying to develop new-generation echo sounders with such capabilities.

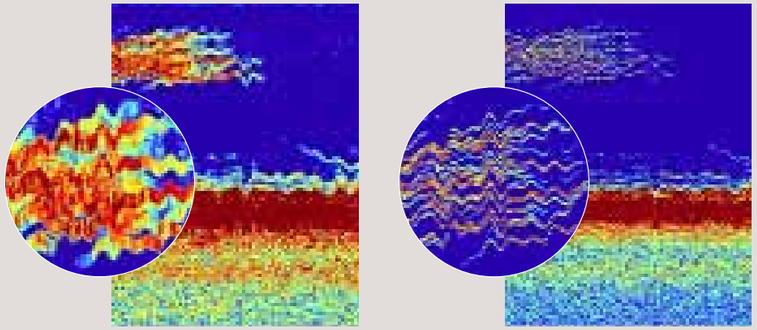
A MAJOR FISHERIES ACOUSTICS company called SIMRAD, based in Oslo, Norway, has developed a multibeam echo sounder called the ME70. This system operates in the 70- to 120-kHz frequency range, not at a single frequency. The frequency response of different sizes and species of fish can be identified using the broadband frequency response from the fish. SciFish model 2100, from Scientific Fishery Systems, Anchorage, AK, uses a 60- to 120-kHz frequency to achieve a broadband response from fish. The device was tested on free-swimming alewives, rainbow smelt, and bloaters in the Great Lakes of North America. A computer neural network was set up to learn the echoes produced by different species. Tests show that the device could identify some lake fish with 80 percent accuracy.

Broadband dolphin echolocation signals were used to measure the backscatter (echoes that travel away from the source of the sound) of marine creatures. The echoes from myctophids and shrimp usually had two highlights, one from the surface of the creature nearest the echo sounder, and a second that was probably from the signal propagating through the body of the creature and reflecting off its opposite surface. The squid echoes consisted mainly of a single highlight but sometimes had a low-amplitude secondary highlight.

The very high resolution of a short-pulse echo sounder worked well in distinguishing between individual fish in a school of Japanese anchovy. This system, called "a dolphin sonar simulator," projects sonar signals of a bottlenose dolphin and has a broadband transducer and receiver adapted for 70 to 120 kHz. Even in a dense group of the fish, many distinctive traces could be recognized by the dolphin mimetic sonar, whereas the conventional echo sounder provided a relatively low-resolution image of the fish school. Using high spatial resolution and broadband echo characteristics, fish size and species identification will be possible even in a dense group of mixed fish.

DOLPHIN SONAR SIMULATOR
The broadband echo sounder, which simulates dolphin sonar, can distinguish between fish with much greater accuracy than conventional echo sounders can. Simply by zooming in on the images of a school of Japanese anchovy (Engraulis japonica) taken by a conventional echo sounder and the dolphin sonar simulator (right), we can see that each trajectory of swimming fish can be recognized by the dolphin sonar simulator, but the conventional echo sounder gives only a limited-resolution image and cannot discriminate between each fish.

COMPARISON OF ECHOGRAM IMAGES OF JAPANESE ANCHOVY



Conventional echo sounder | Dolphin mimetic sonar

CONCLUSION

Accurate classification and identification of underwater targets is vital, not only for fisheries surveys but also for underwater security measures. To achieve this, researchers have recently attempted to mimic dolphin sonar. The next step is to identify key acoustic characteristics, which are probably embedded within each echo, to distinguish one target from another. Analyzing spatial and frequency structures of echoes from different types of targets will also be helpful.

▶ We are currently learning to distinguish between sea creatures in the same way dolphins do. For example, we now know that squid emit echoes comprising a single highlight with an occasional softer, secondary highlight.

Broadband sonar is more strongly affected by noise contamination than conventional narrowband sonar is, and countermeasures for noise reduction are still poor, so engineers will need to improve broadband transmission efficiency and reduce noise produced by ships. To make broadband sonar viable as a commercial product, we need to overcome the current system's large size and huge energy consumption. In the meantime, development of a broadband sonar system that is able to find and classify invisible targets will require more research on the mechanisms of dolphin sonar, which have evolved over time to ensure dolphins' survival underwater. Fortunately, elementary technologies for simulating dolphin broadband sonar are now available due to the rapid progress of technology. Broadband fine-resolution sonar, inspired by dolphins, is therefore set to become an invaluable tool for "seeing" underwater objects in the future.

BULLETPROOF FEATHERS

How Science Uses Nature's Secrets to Design Cutting-Edge Technology

EDITED BY **ROBERT ALLEN**

Fabrics that are not only stain resistant but actually clean themselves. Airplane wings that change shape in midair to take advantage of shifts in wind currents. Hypodermic needles that use tiny serrations to render injections virtually pain free.

Though they may sound like the stuff of science fiction, in fact such inventions represent only the most recent iterations of natural mechanisms that are billions of years old—the focus of the rapidly growing field of biomimetics. Based on the realization that natural selection has for countless eons been conducting trial-and-error experiments with the laws of physics, chemistry, material science, and engineering, biomimetics takes nature as its laboratory, looking to the most successful developments and strategies of an array of plants and animals as a source of technological innovation and ideas. Thus the lotus flower, with its waxy, water-resistant surface, gives us stainproofing; the feathers of raptors become transformable airplane wings; and the nerve-deadening serrations on a mosquito's proboscis are adapted to hypodermics.

With *Bulletproof Feathers*, Robert Allen brings together some of the greatest minds in the field of biomimetics to provide a fascinating—at times even jaw-dropping—overview of cutting-edge research in the field. In chapters packed with illustrations, Steven Vogel explains how architects and building engineers are drawing lessons from prairie dogs, termites, and even sand dollars in order to heat and cool buildings more efficiently; Julian Vincent goes to the very building blocks of nature, revealing how different structures and arrangements of molecules have inspired the development of some fascinating new materials, such as waterproof clothing based on shark skin; Tomonari Akamatsu shows how sonar technology has been greatly improved through detailed research into dolphin communication; Yoseph Bar-Cohen delves into the ways that robotics engineers have learned to solve design problems through reference to human musculature; Jeannette Yen explores how marine creatures have inspired a new generation of underwater robots; and Robert Allen shows us how cooperative behavior between birds, fish, and insects has inspired technological innovations in fields ranging from Web hosting to underwater exploration.

A readable yet authoritative introduction to a field that is at the forefront of design and technology—and poised to become even more important in the coming decades as population pressures and climate change make the need for efficient technological solutions more acute—*Bulletproof Feathers* offers adventurous readers a tantalizing peek into the future, by way of our evolutionary past.

ROBERT ALLEN is professor of biodynamics and control at the Institute of Sound and Vibration Research, University of Southampton, and the founding editor of the journal *Bioinspiration and Biomimetics: Learning from Nature*.

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