September 22, 2025

Master Degree in Bionics Engineering

Course of Principles of Bionics and Biorobotics Engineering

Lesson title:

The Birth of Bionics

Prof. Donato Romano (donato.romano@santannapisa.it)

THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

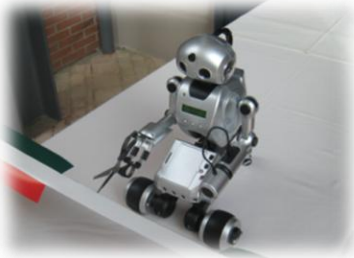
Aims of the Master Degree (and of this course)

Train a new generation of students, to make them able to face frontier engineering problems, by combining science and hi-tech

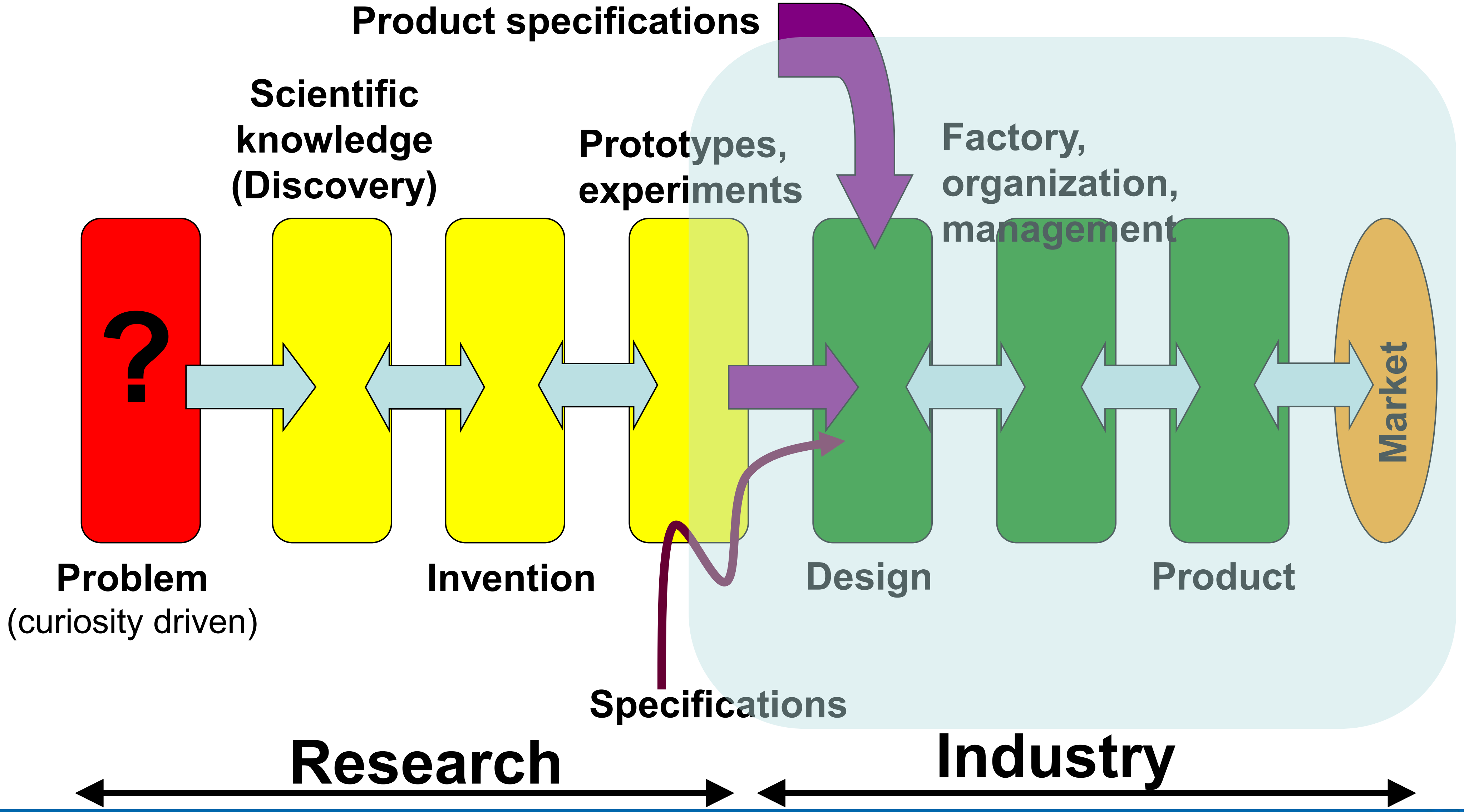
Frontier research
(University and industry)

M.Sc. in Bionics Engineering

Product innovation
(Industry)



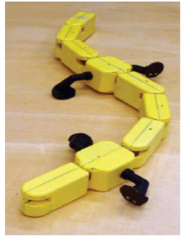
Going beyond traditional engineering education



From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model

Auke Jan Ijspeert,[1*] Alessandro Crespi,[1] Dimitri Ryczko,[2,3] Jean-Marie Cabelguen[2,3]

9 MARCH 2007 VOL 315 SCIENCE www.sciencemag.org



BIOMECHANICS

Jumping on water: Surface tension–dominated jumping of water striders and robotic insects

Je-Sung Koh,[1,2*] Eunjin Yang,[3*] Gwang-Pil Jung,[1] Sung-Pill Jung,[1] Jae Hak Son,[4] Sang-Im Lee,[4,5] Piotr G. Jablonski,[4,6] Robert J. Wood,[2] Ho-Young Kim,[3,5†] Kyu-Jin Cho[1,5†]

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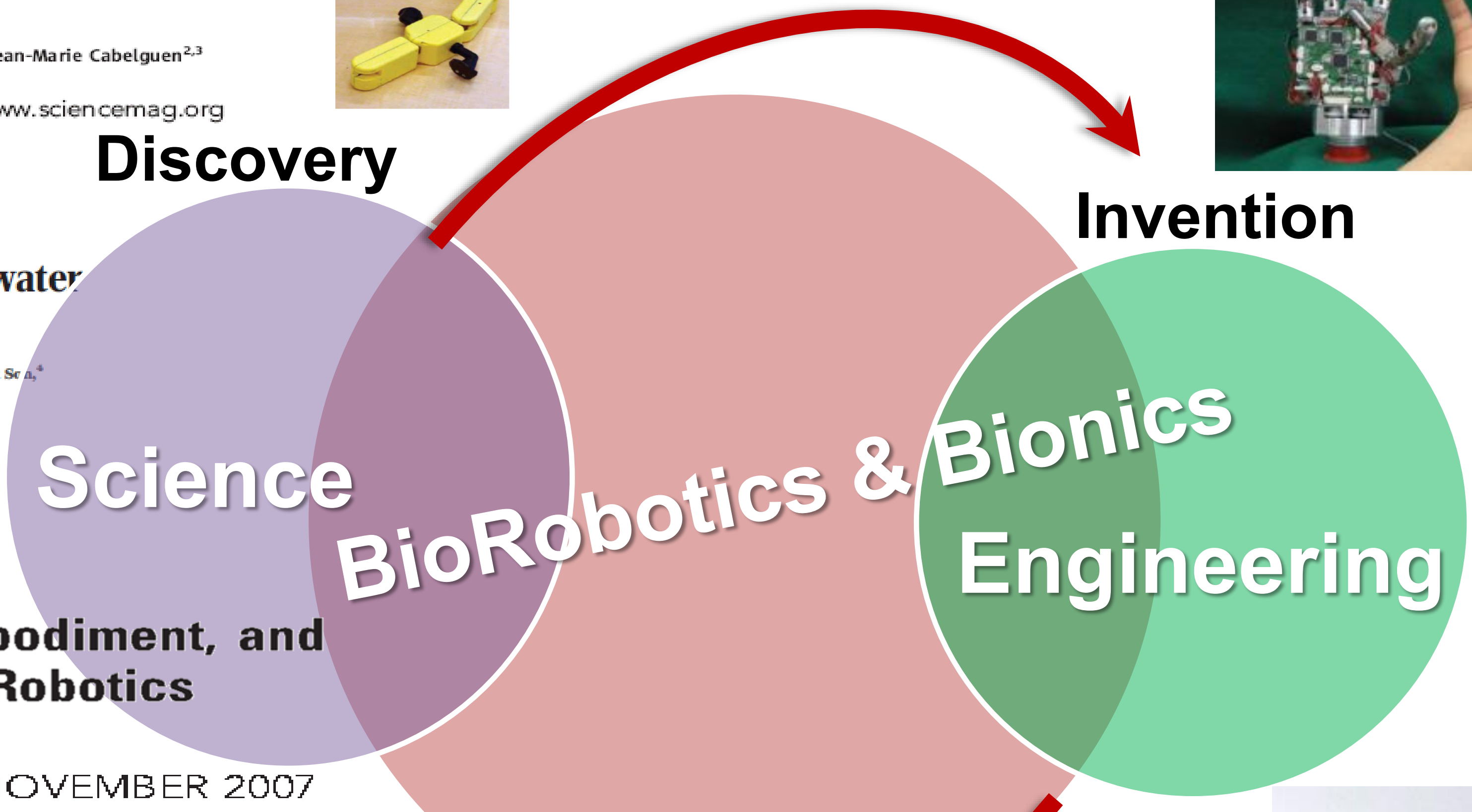
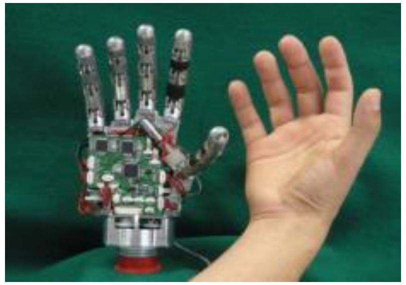


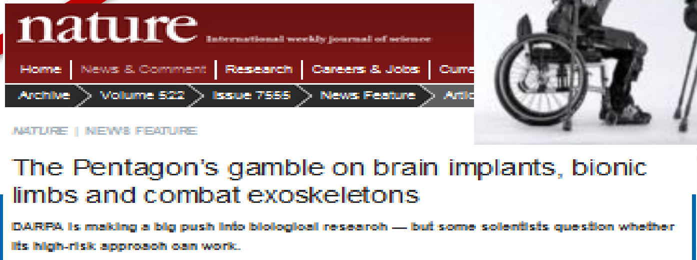


June 2015

Self-Organization, Embodiment, and Biologically Inspired Robotics

Rolf Pfeifer,[1*] Max Lungarella,[1] Fumiya Iida[1,2]

SCIENCE VOL 318 16 NOVEMBER 2007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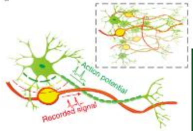
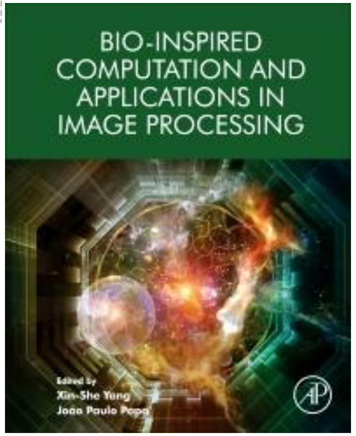
NATURE | NEWS FEATURE

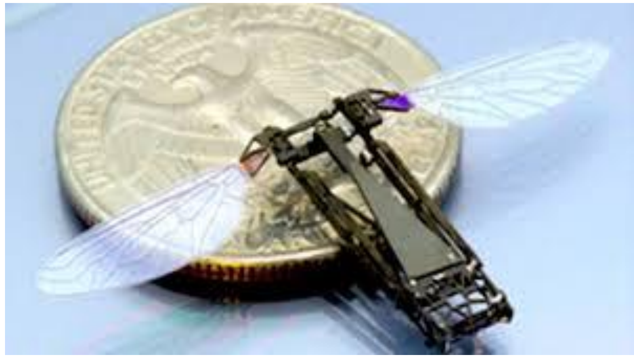
The Pentagon's gamble on brain implants, bionic limbs and combat exoskeletons

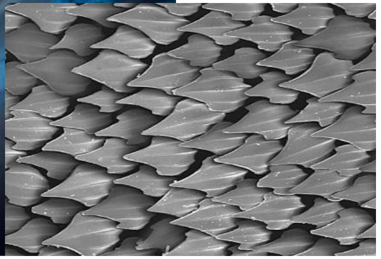
DARPA is making a big push into biological research — but some scientists question whether its high-risk approach can work.

Current applications of animal inspired bionic technologies

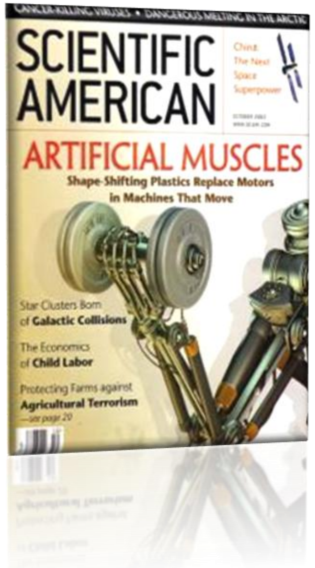


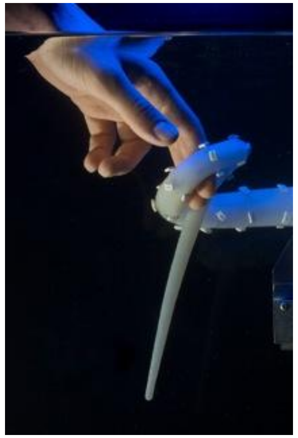


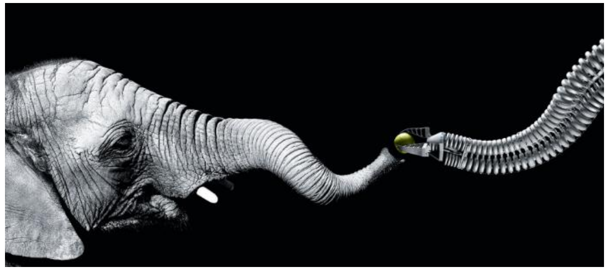


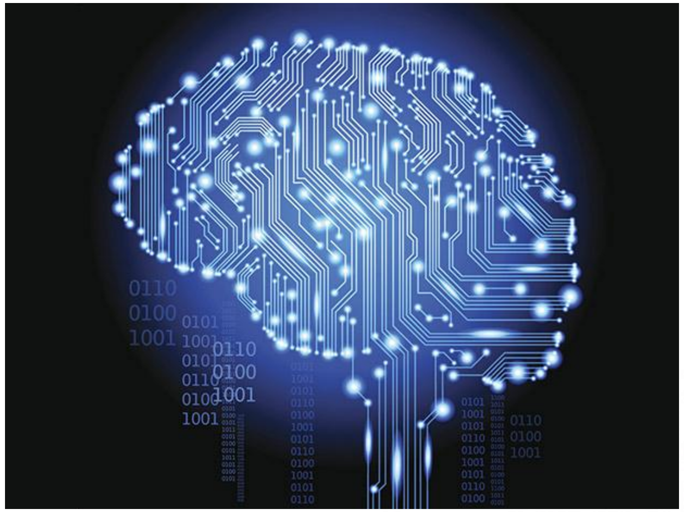


Shark skin-inspired swimsuits









September 25, 2025

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From Swimming to Walking with a Salamander Robot Driven by a Spinal Cord Model

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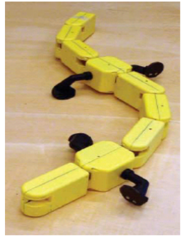

BIOMECHANICS

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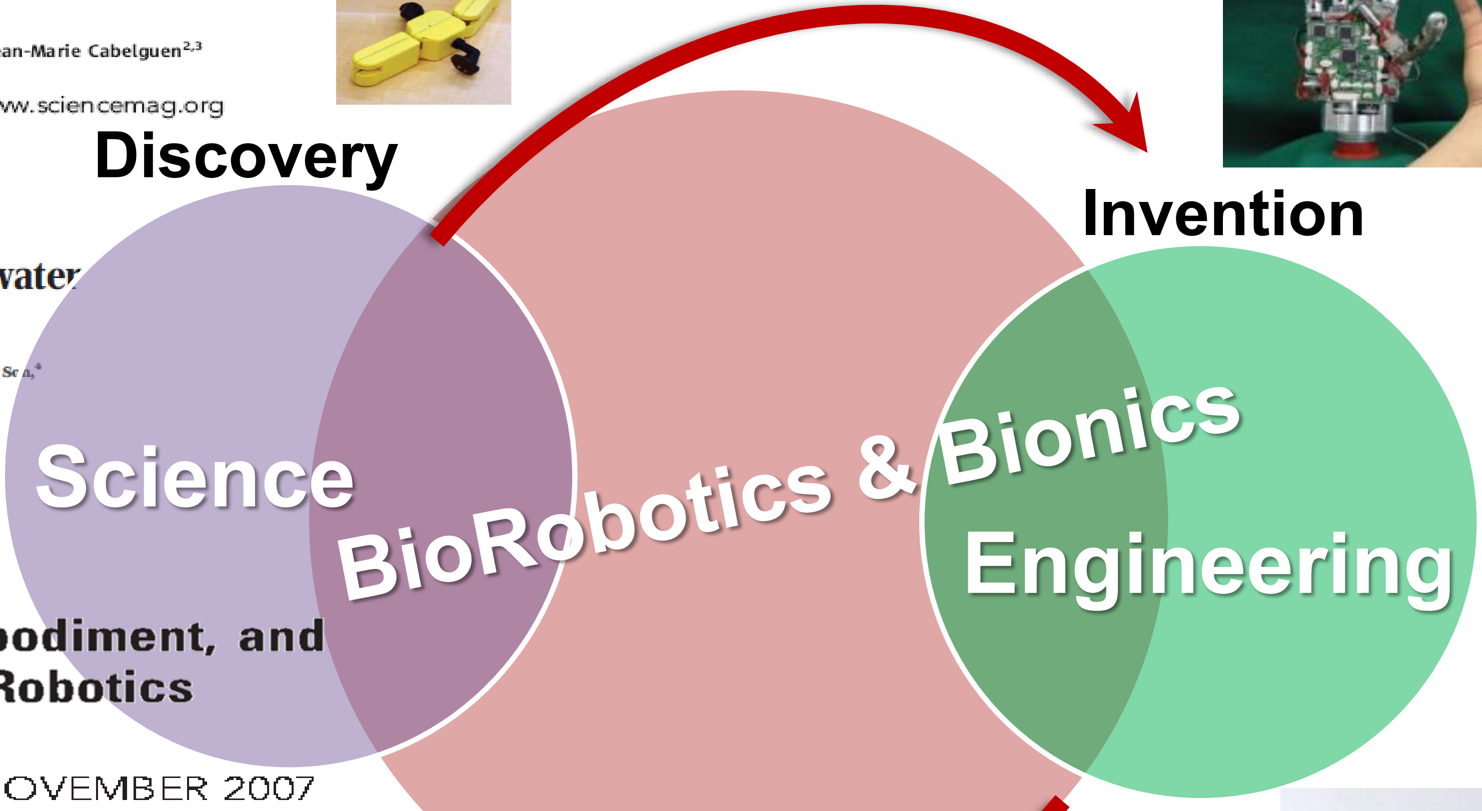

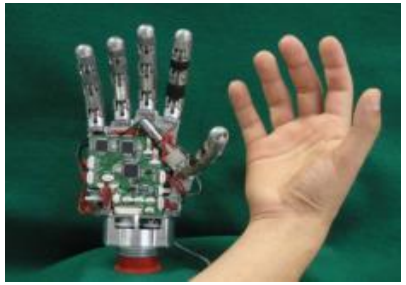

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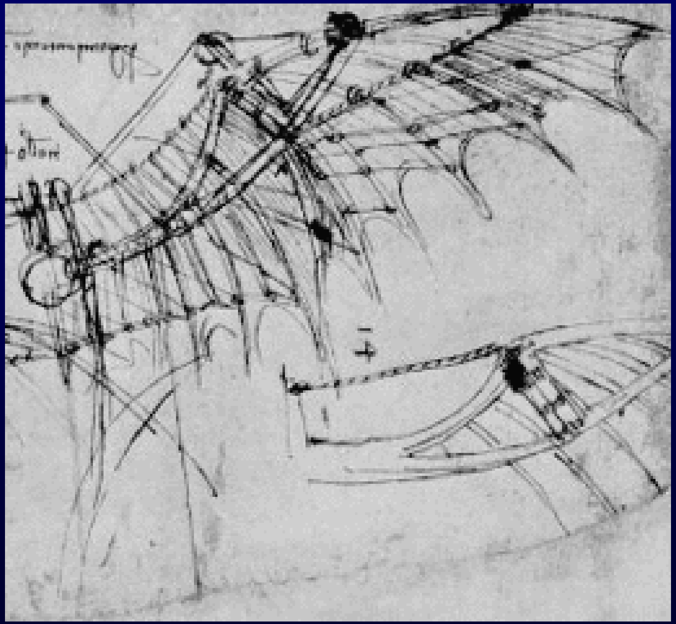
NATURE | NEWS FEATURE

The Pentagon's gamble on brain implants, bionic limbs and combat exoskeletons

DARPA is making a big push into biological research — but some scientists question whether its high-risk approach can work.

Chinese tried to make an artificial silk more than 3000 years

Leonardo da Vinci studied bird flight and designed some machines

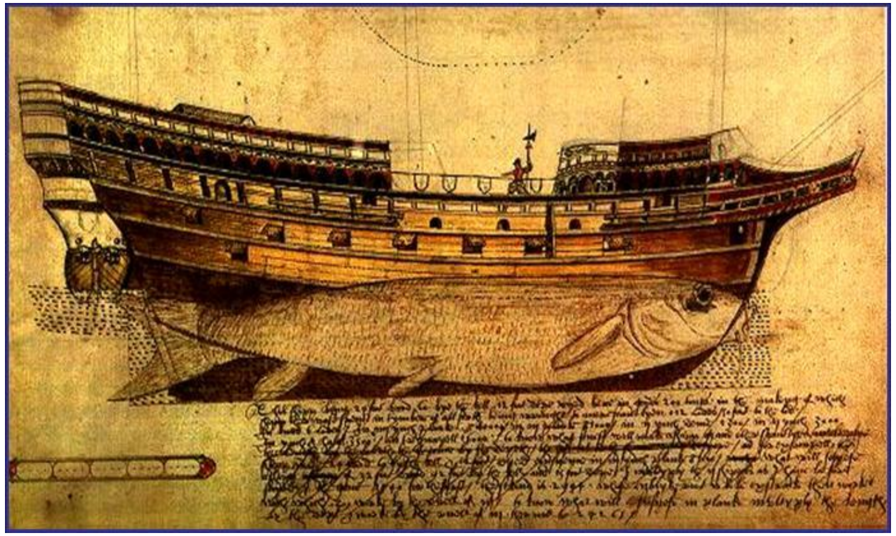


The underwater hulk of Baker's galleon

A very early example shows natural abstraction, not copy of nature

BIOLOGY:
The bodies of fast-swimming fishes appear **flow optimized**. Therefore it would make sense to shape, for example, the underwater hulk of a ship after the form-model of a particular fish.

HISTORY:
The ship construction master **Matthew Baker** drafted a new galleon-type (1576) that reduces the water-drag and, achieves higher speed, mobility and course-stability.



Sketch with plotted fish by Matthew Baker

A galleon with “*codfish head and mackerel tail*“, that is a generally abstracted
shape of a fast-swimming, big sea fish. For the **first time** M. Baker has integrated in the construction of ship hulks also practical nature studies.

Barbed wire is a bionic invention

BIOLOGY:

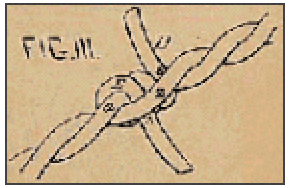
The Osage-orange, *Maclura pomifera* was used in the hedge rows of cattle farmers **prior to the advent of steel**, barbed wire fencing. They would have been planted them a few feet apart, in straight rows and the limbs would have entangled themselves together making an impenetrable hedgerow, by cattle or man.

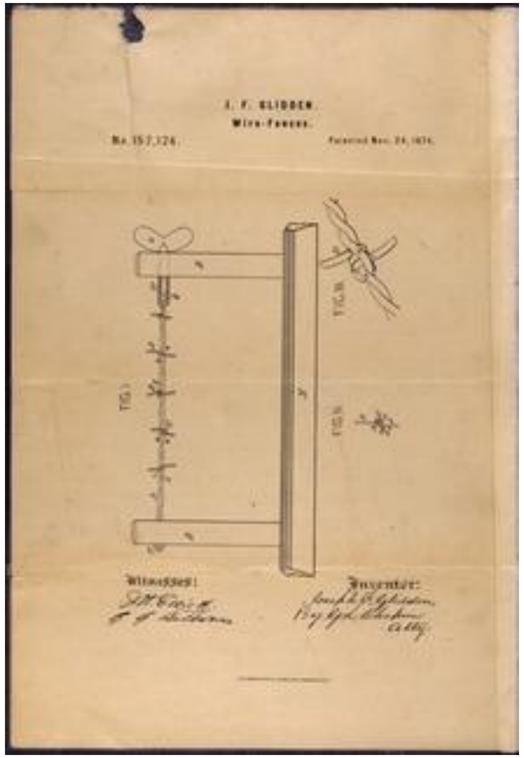
PRINCIPLE:

With the first patent of a “thorny wire” (Mike Kelly, 1868), the sharp thorns close to the basis of an Osage-branch were imitated. They were built of duplicate-sharpened, thorn-like metal-platelets between two wire-strings.

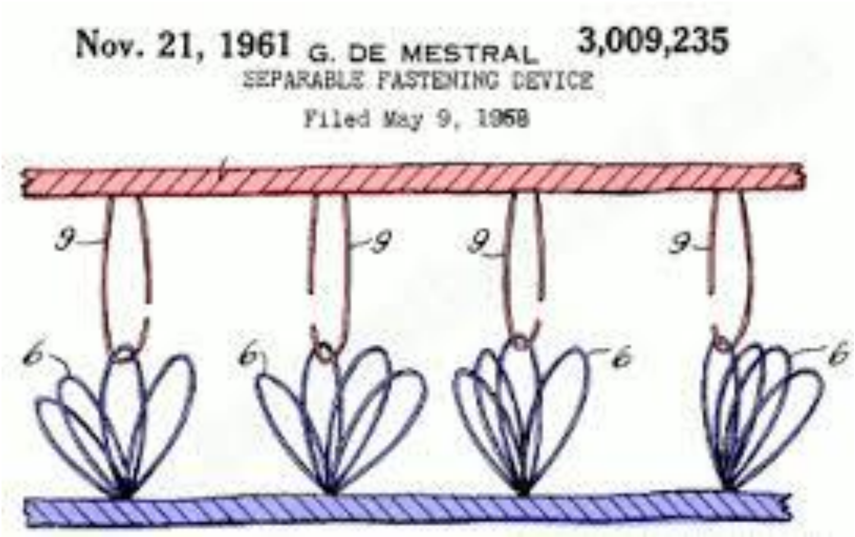
In 1974 The Glidden-wire (Joseph F. Glidden), was patented and it was more practicable than the thorny wire. This sharp metal-platelets, tied-in by hand, were replaced by mechanically plaited double-thorns

Patent drawing for Joseph F. Glidden’s improvement to barbed wire

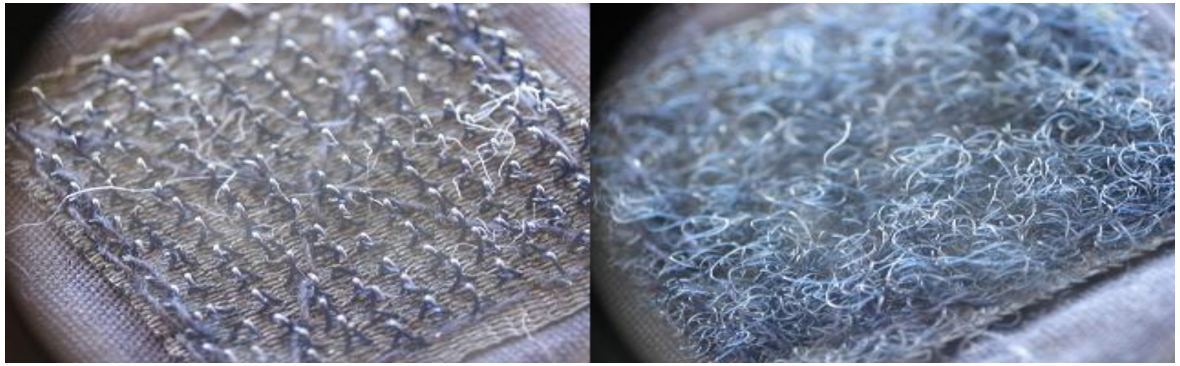




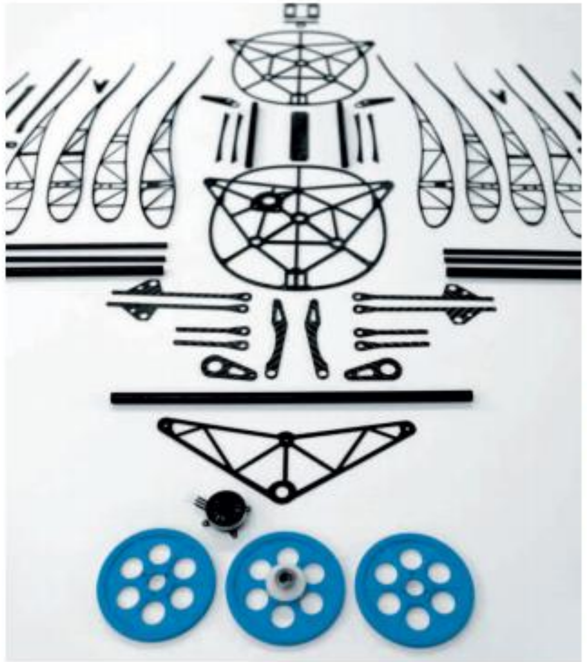
Velcro resulted in 1948 from a Swiss engineer, George de Mestral, noticing how the hooks of the plant burrs (*Arctium lappa*) stuck in the fur of his dog.



The name "Velcro" comes from the French: "velour" - fluffy material and "crochet" hook. How simply the principle: the development of a working hook (A) and wool-band (B) lasted more than 10 years



FESTO



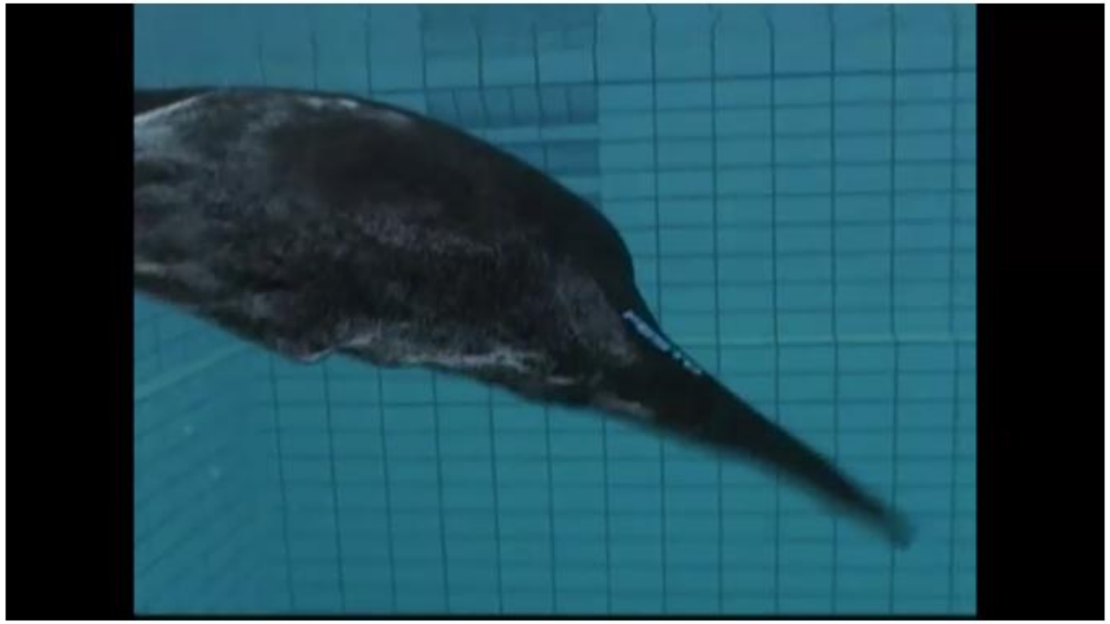
Technical data

Torso length:	1.07 m
Wingspan:	2.00 m
Weight:	0.450 kg
Structure:	lightweight carbon fibre structure
Lining:	extruded polyurethane foam
Battery:	lithium polymer accumulator, 2 cells, 7.4 V, 450 mA
Servo drive:	2x digital servo unit with 3.5 kg actuating force for control of head and tail sections 2x digital servo units for wing torsion, with 45 degree travel in 0.03 s
Electrical power requirement:	23 W
Microcontroller:	MCU LM3S811 32-bit microcontroller@50 MHz 64 kByte flash, 8 kByte RAM
Radio transmission:	868 MHz/2.4 GHz two-way radio transmission based on ZigBee Protocol
Motor:	Compact 135, brushless
Sensors:	Motor positioning 3x TLE4906 Hall sensors
Accelerometer:	LIS302DLH
Power management:	2x LiPo accumulator cells with ACS715 voltage and current monitoring
LED activation:	TPIC 2810D

Aqua_ray

Inspired by the manta ray

Whether by means of dynamically beating wings or elegant gliding: the Aqua_ray uses its functional anatomy to manoeuvre through the water in an easy and energy-efficient manner. The artificial fish is not only based on the real manta ray in terms of its shape, however. Its motion pattern closely approximates its natural model.



Fluidic Muscle and Fin Ray Effect® combined

For the central propulsion and control unit for the Aqua_ray, Festo uses the Fluidic Muscle: two pairs of muscles working in opposite directions, combined with the Fin Ray Effect®, for the beating wing drive in the two wings. The structure with Fin Ray Effect® is a design derived from the functional anatomy of a fish fin. It enables the fin drive of its natural role model to be imitated almost perfectly.

Science Robotics

RESEARCH ARTICLE | ANIMAL ROBOTS

Tuna robotics: A high-frequency experimental platform exploring the performance space of swimming fishes

J. Zhu[1], C. White[1], D. K. Wainwright[2], V. Di Santo[2,*], G. V. Lauder[2] and H. Bart-Smith[1,†]

+ See all authors and affiliations

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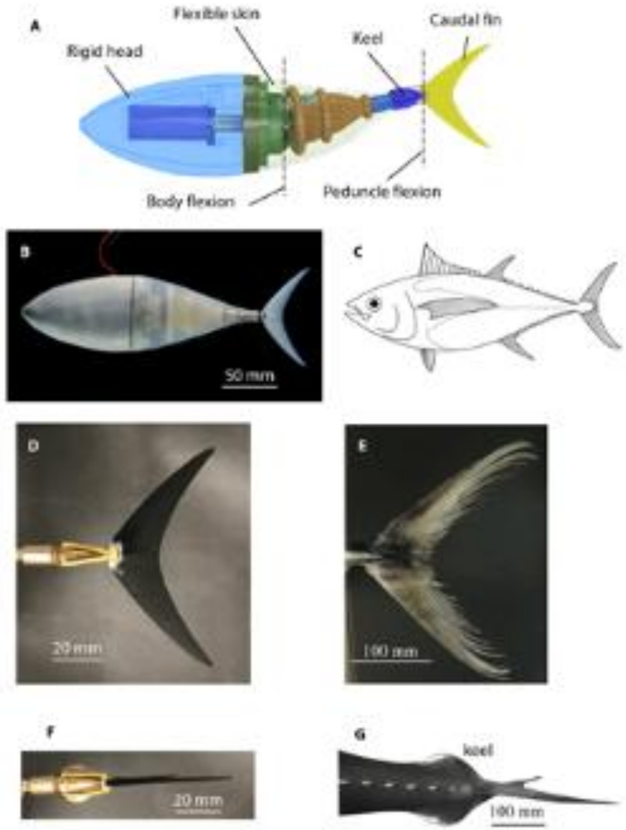
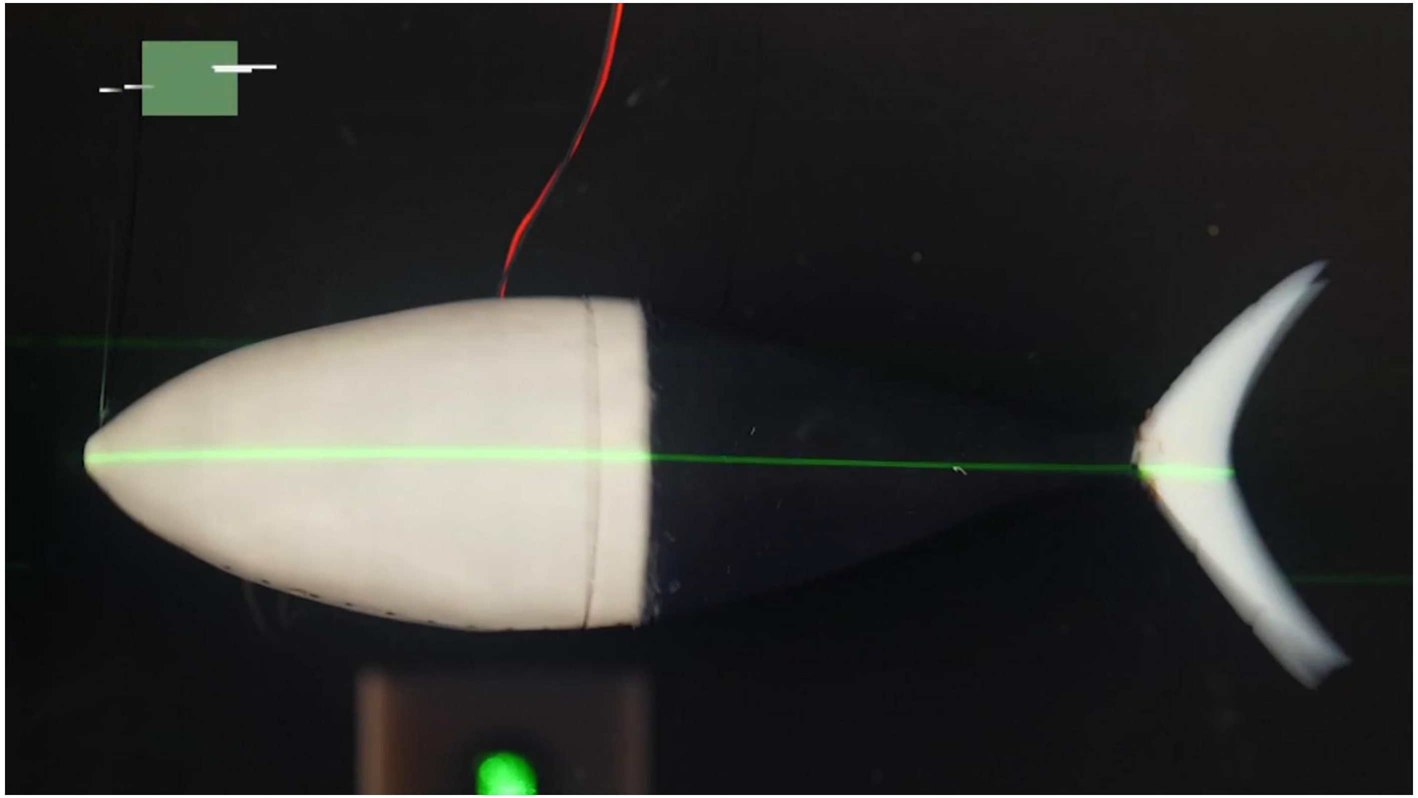




Design of the Tunabot platform.

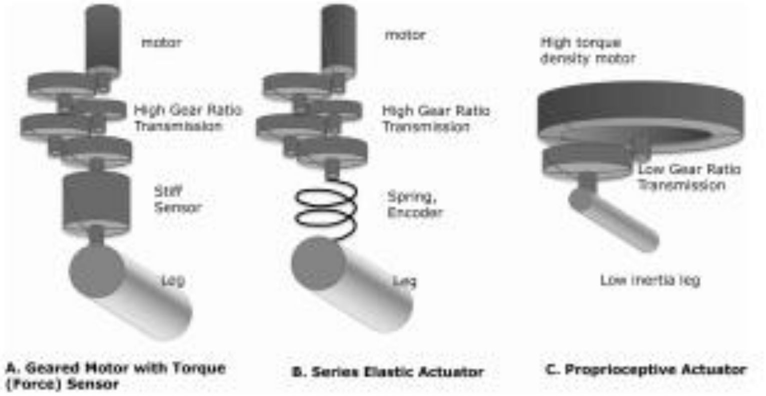
(A) Overall Tunabot body plan showing the major components of the tuna-like mechanical system. The Tunabot is 255 mm in total length. Body shape (B) was based on a simplified yellowfin tuna (*T. albacares*) body plan (C) and features a streamlined shape with a narrow caudal peduncular region anterior to the tail. During testing, the Tunabot was suspended by two thin vertical threads, and one lateral thread at the nose prevented extreme motion in the event of failure but did not restrict lateral Tunabot oscillation during swimming. The power cable (red) is visible and also did not restrict robot motion in any way. Tunabot tail morphology (D) was manufactured on the basis of the yellowfin tuna tail (E). The tail is supported by a metal peduncle with lateral keels (F) designed from the lateral keels of yellowfin tuna (G). Images of tuna in (E) and (G) are from a fish about 1 m in length.

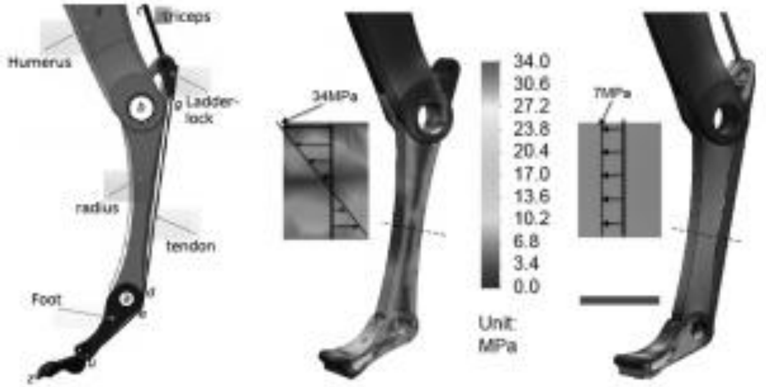
The MIT Cheetah, an Electrically-Powered Quadrupedal Robot for High-speed Running

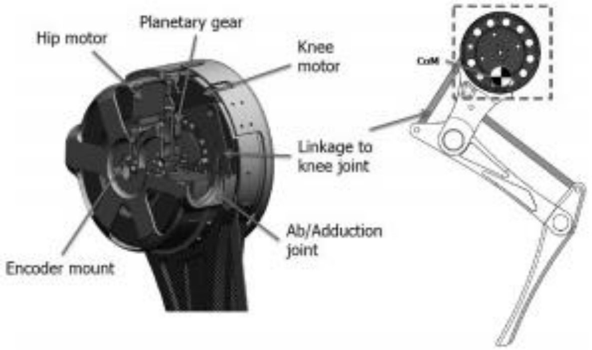
Hae-Won Park* *and* Sangbae Kim* *The Department of Mechanical Engineering, Mas

2. Brief Overview of the Robot

The MIT Cheetah is a quadrupedal robot comprised of 14 links including four legs and a two-segmented body. Each leg of the MIT Cheetah consists of three links, and the motions of the first and the last link from the shoulder are kinematically tied to be parallel to each other by pantographic leg design, resulting in two degree of freedom links. A low-power servo actuator controls the third degree of freedom of a leg, ab/adduction motion. A flexible spine is made of segmented vertebrae and urethane rubber disks, which allows body articulation. The motion of the spine is coupled with motions of two rear shoulder joints through the differential gear train. Due to this coupling through the differential, the spine bends and extends as two rear shoulder joints move in-phase as in galloping gait, whereas the spine does not move if motions of two rear shoulder joints are out-of-phase as in trot gait. The robot weighs 32 kg, and it is approximately 70 cm tall, 23 cm wide, and 1m long (See **Fig. 1**).







ROBIRD

System

The key feature of the Robird is its flapping-wing flight. Both thrust and lift are produced by a combination of the shape and flexibility of the wings and the mechanism that not only flaps the wings (a plunging motion), but also changes their angle of attack (pitching) during the wing stroke. The wings and tail have control surfaces for stabilization; the mechanism (Figure 2) and avionics for the autopilot reside inside the hull (Figure 3).

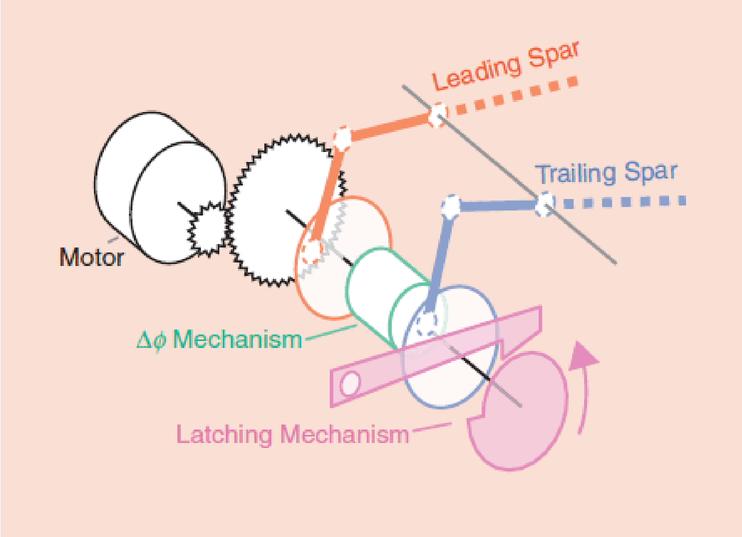
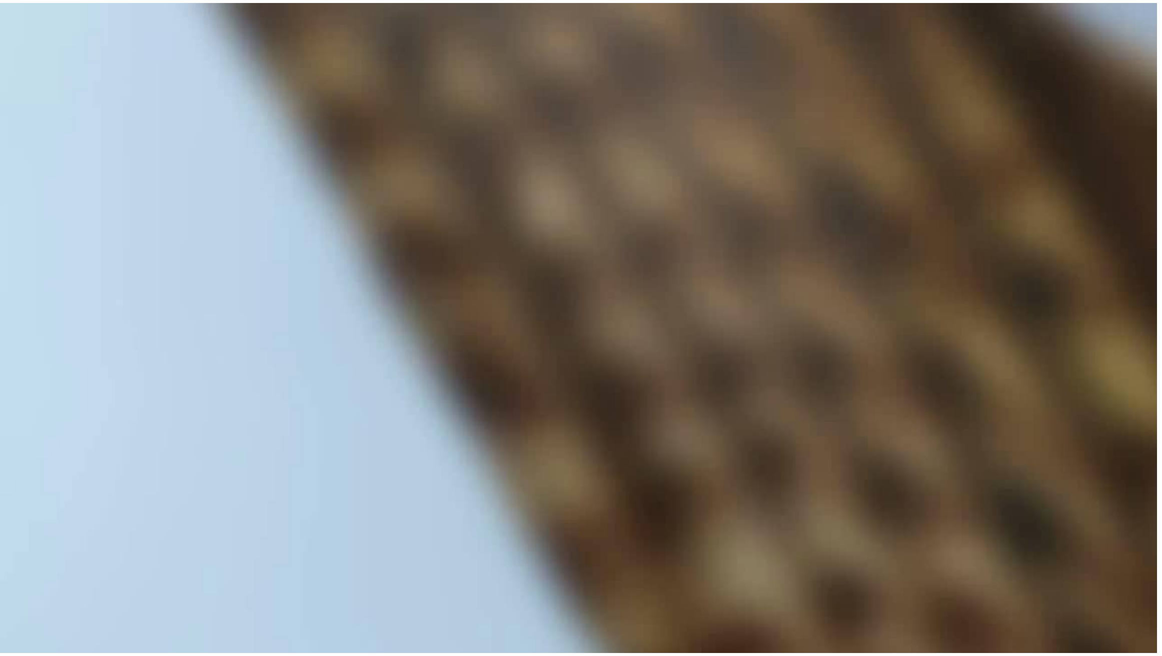


Figure 2.
A schematic drawing of the wing mechanism. The leading and trailing edge of the wing are driven with a phase difference of $\Delta\phi \in [0^{\circ}, 15^{\circ}]$. Their rotation is transformed to a flapping motion of the wing through a connection rod mechanism for each driving spar. If the motor is stopped at the right time, lift pressure pushes the notch wheel against the pawl (latching mechanism), which allows the Robird to soar with the motor turned off.



Aerodynamic parameters for the glide ratio calculation of the Robird.

Parameter	Value	Description
$C_{D,0}$	0.08	Drag Coefficient $c_L = 0$
e	0.81	Oswald Span Efficiency Factor
b	1.12	Wingspan, m
S	0.145	Wing Surface Area $[m^2]$

Boston Dynamics

SPOT®

A nimble robot that climbs stairs and traverses rough terrain with unprecedented ease, yet is small enough to use indoors. Built to be a rugged and customizable platform, Spot autonomously accomplishes your industrial sensing and remote operation needs.

MOBILE

Spot can go where wheeled robots cannot, while carrying payloads with endurance far beyond aerial drones.

SPEED	RUNTIME	BATTERY
1.6 m/s	90 min	Swappable

PERCEPTIVE

Spot uses stereo cameras to avoid obstacles and people as it moves through dynamic work sites.

VISION
360°

DURABLE

Spot is built to withstand dusty and wet industrial environments. Crash protection keeps Spot safe.

INGRESS PROTECTION	OPERATING ENVIRONMENT
IP54	-20°C to 45°C

CUSTOMIZABLE

Spot's flexible payload interface and accessible API enable third parties to develop the next generation of robotic applications.

PAYLOAD CONNECTION	PAYLOAD CAPACITY
DB25	14 kg

SENSING

Captures spherical images and comes with an optional PTZ camera with 30x optical zoom for detailed inspections.

COMPUTING

Allows for faster prototype development via an onboard processing unit.

MANIPULATION

Enables mobile manipulation for tasks like opening doors and grasping objects.

POWER

Provides regulated power and an ethernet port for easy payload integration.

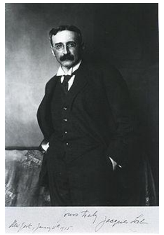
The origins: Bionics epistemology*

* Epistemology, from Greek. ἐπιστήμη «knowledge» and λόγος "speech" used in 1854 by Scottisch philosopher J. F. Ferrier – In XIX century philosophy it represents a part of gnoseology, dealing with methods and fundaments of scientific knowledge. In a modern sense, epistemology refers to critical investigation on structure and methods (observation, experimentation and inference) of sciences. Synonim of Phylosophy of Science.

Proto-Cybernetics (J. Loeb 1905, H. S. Jennings 1906)

Mechanicism Vs. Functionalism for studying the behavior of living organisms

If a machine is implemented on the basis of a theory of behavior, and ***it behaves according to what this theory allows to predict***, this test reinforces the proposed theory



Jacques Loeb

Herbert Spencer Jennings

Cybernetics (Rosenblueth, Wiener, Bigelow 1943)

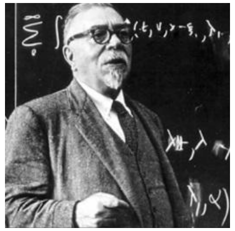
Unified approach to the study of living organisms and machines

Purposive adaptive behaviors (in animals and humans) are produced by *feedback machines (teleology)*

Machines as 'material models' useful for testing scientific hypotheses

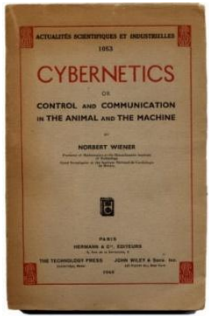
Machines are used for SCIENCE

Arturo Rosenblueth



Norbert Wiener

Julian Bigelow



Datteri, E., Tamburrini, G., "Bio-robotic experiments and scientific method", in Magnani, L., Dossena, R. (eds), *Computing, Philosophy and Cognition*, College Publications, London, 2005.

The context in which the first wave of bionics originated

Bionics during the Cold War (1947–1962)

The birth of Bionics

Bionics as an inter-science discipline officially dates back to **1958** when **Major J. E. Steele** coined the term making reference to a research program at the **Wright-Patterson Air Force Base in Dayton, OH, USA**

Jack E. Steele

Wright-Patterson Air Force Base

Steele used the term **bionics** to mean "**a life-like system that copies some functions and characteristics of a natural system**"

Science AAAS

Meetings

Bionics

The unities underlying the behavior of animals, men, and machines were brought into clearer focus at a national symposium held 13–15 September 1960 in Dayton, Ohio. The meeting, under the sponsorship of the Wright Air Development Division of the United States Air Force, was attended by approximately 700 persons. Thirty invited speakers reported new developments concerning methods of information handling used by living systems and artificial models of such systems. The magnitude of the recent advances so impressed the participants that they virtually demanded that such a meeting be made a regular event. This report is based entirely on my notes; I apologize for any errors of fact or interpretation, and for not mentioning many talks because of lack of space.

At the start, H. E. Savely of the Air Force Office of Scientific Research pointed out three aspects of living systems which are worthy of study for incorporation into artificial systems: (i) the extreme sensitivity of certain receptor organs—for example, the ability of certain fish to detect a change in the electric field in the water around them of as little as 0.003 μv/mm; (ii) the ability of even simple living brains to integrate the activity of many sensor and effector organs; (iii) the ability to retrieve information rapidly in the central nervous system; and (iv) the ability to store information at molecular levels, even for periods of generations, as in the chromosomes. An example of the successful use of a living system as a prototype for an artificial system is the application in an optical ground-speed indicator for airplanes of the simple principle in the beetle's visual system that provides information on velocity.

H. E. Savely cautioned (i) that as long as we lack fundamental understanding of the laws of organized complexity, it may not be possible to duplicate the living system; (ii) that nature is limited simply to building on and modifying pre-existing systems and that the living system therefore may not provide the most economical approach to a particular information-handling problem; and (iii) that it is common for the physical scientist to think that he can take a quick look at some biological system, work out the principles in a very short time, and then apply them to the design of some artificial system. Not only is he mistaken in this belief but he is very much like Brer Rabbit attacking the Tar Baby. The harder he attacks the problems of biology the more deeply does he become enmeshed, so that he soon finds himself unable to drop them.

An analysis of the relatively simple servomechanism controlling the size of the pupil of the human eye was presented by Lawrence Stark, now of the Massachusetts Institute of Technology. This paper and one other were the only reports dealing directly with the information-handling mechanisms of living systems—evidence perhaps of the difficulty of such an approach. The other talks dealt with the design of artificial systems. E. E. Loebner of RCA Research Laboratories pointed out that man, because he has few outputs (muscles), has built only a few information inputs into the gear he controls, to match his few outputs. This restriction on the number of inputs has been carried over into equipment not under human control. It would often be preferable to give such equipment multiple inputs, such as man has in his sense organs.

The general logical operations that a computer must perform in order to behave like an organism were described by Peter M. Kelly of Aeronutronics. It must take inputs from a sensory field, code them into groups, act on them by some internal logic, code the outputs, and carry out responses in terms of this output code. The coding of the sensory input to the internal logic can be fixed in advance—that is, preorganized. It is also possible to design machines which are self-organized—that is, capable of learning how to code their sensory input and their output so as to achieve the desired responses to particular sensory situations. Kelly, and also Walter Reitman of Carnegie Institute of Technology, discussed the design of such machines and gave examples of existing machines in which the two types of design are used. (Could it be that when we intuitively judge one type of organism to have more "consciousness' than another, the distinction in physical terms is that it has a greater capacity for self organization?)

W. P. Tanner of the University of Michigan argued that the human being is not completely preorganized so as to give a fixed response for a particular sensory input but is capable of self-organization. Therefore, the human being subjected to psychophysical tests should not be considered to have a sensory threshold but should be treated as a computer which is testing the statistics of the test situation and making decisions which optimize some aspect of that situation. Tanner is analyzing such performances of human beings in auditory test situations.

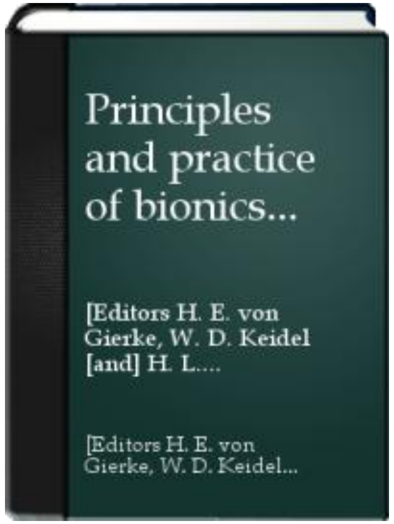
The problem of designing a machine which can differentiate or recognize one out of all possible sensory functions was discussed by Seymour Papart of the National Physical Laboratory, Teddington, England. The problem is simplified by the fact (i) that the input functions possible are only a portion of all functions, and (ii) that as the number of dimensions of the input functions increase, the chance of separating any two input functions increases, even with a simple machine. He has roughly estimated that one human being during his lifetime could learn up to 10^{8} particles of information. This much learning could be handled by any of the systems of self-organization described at the symposium. (Compare this estimate with the estimate of 10^{15} made some years ago by W. S. McCulloch and of 10^{13} to 10^{18} made by H. von Foerster.)

Artificial devices which recognize patterns, including one device capable of recognizing cancerous cells under the microscope, were mentioned by P. Metzelaar of Space Technology Laboratories. Some machines have given performance superior to the human—for example, a checker playing program for the IBM 704 computer. Other machines have been designed that can predict the future of a sequence from its past. Metzelaar suggested that if the design problems can be solved, the future machine will do preliminary pattern transformations on its sensory inputs in order to reduce the amount of information that must be handled and stored. It will also be able to consider its sensory input in either gross outline or fine detail and know which type of consideration is needed, decide how to divide its attention among its different sensory inputs, and know which of various recognition mechanisms it should use.

In a talk that was as remarkable for its witty asides as for its lucid exposition, A. Novikoff of Stanford Research Institute briefly described integral geometry and illustrated its use in the

J.E. Steele. *Bionics Symposium: Living Prototypes – The Key to New Technology*, ed. C.H. Gray. New York, 55–60 (1960)

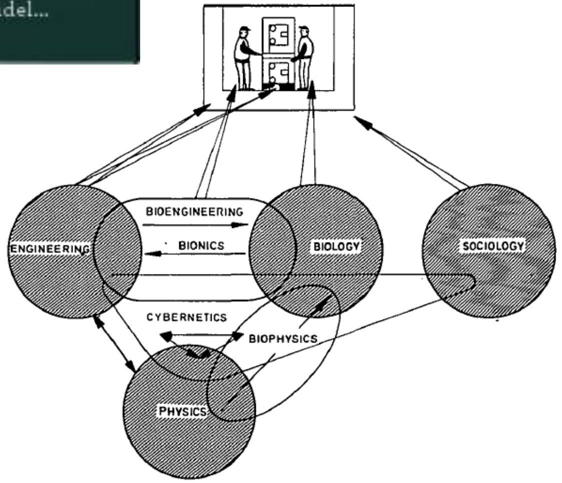
Scientific milestones of Bionics



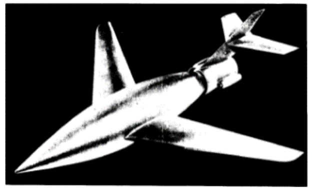
The primary goal of bionics is *"to extend man's **physical and intellectual capabilities** by prosthetic devices in the most general sense, and to replace man by **automata and intelligent machines**"*

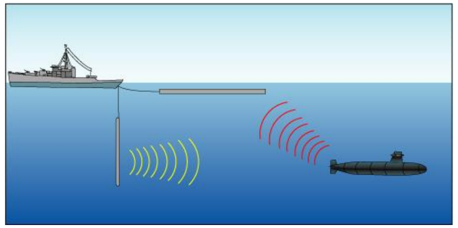
Henning Edgar von Gierke

These objectives were pursued by using models from the animal kingdom…



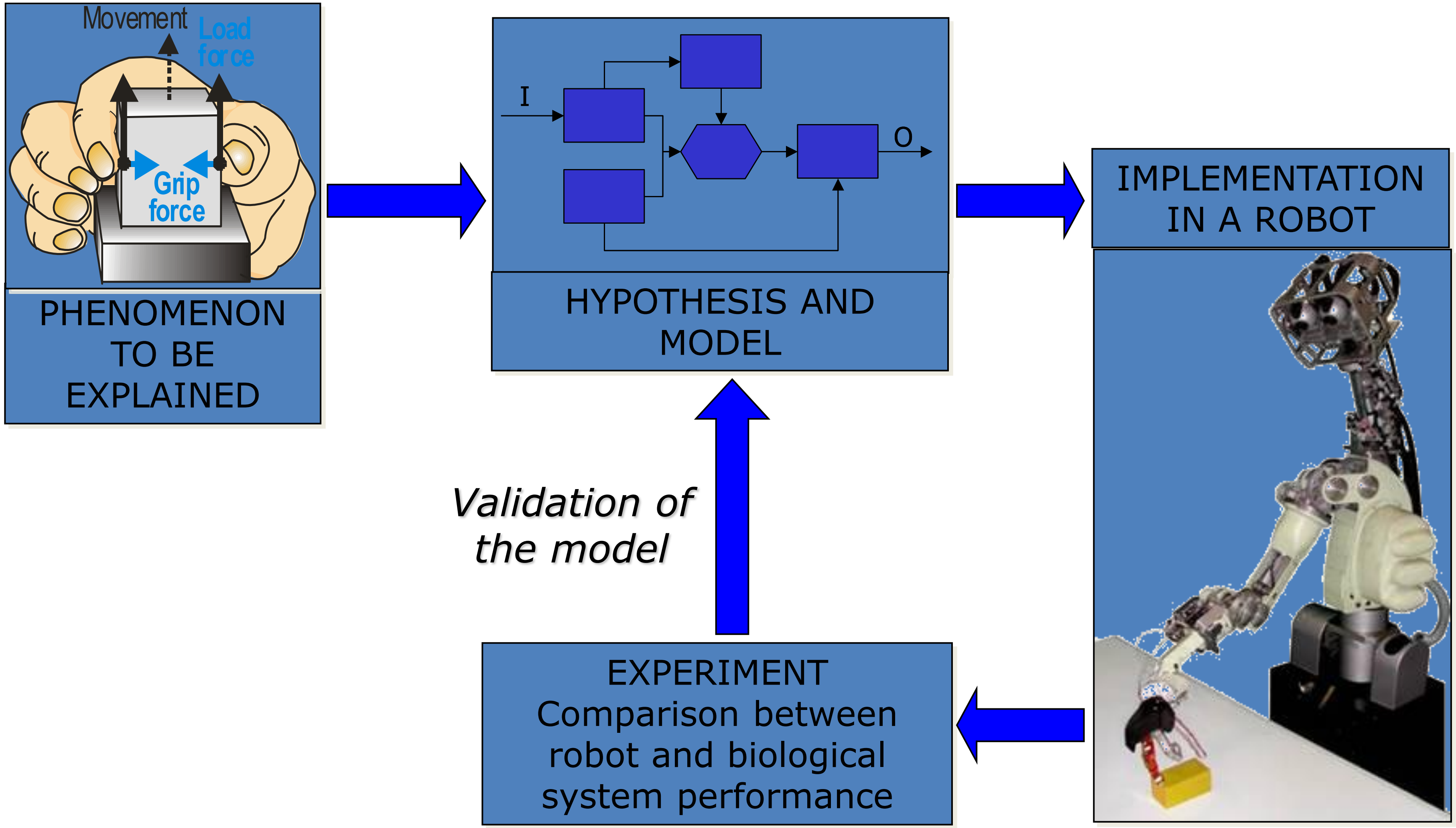
Research efforts were mainly driven by **military applications**





H.E.Von Gierke, W.D. Keidel. Principles and practice of bionics. *Technivision Services* (1970)

Biorobotics Science



This approach can be used for:

Corroboration/falsification

… if the natural and the robotic system behave in the same/different way under the same external and internal circumstances

Deciding between two competing hypotheses

… if the behaviour of the robot built according to the theoretical model M1 is more similar to the target biological behaviour than the behaviour generated by the robot built according to the theoretical model M2

Generating new hypotheses on the functional structure of the biological system

• Barbara Webb, *Biorobotics*, MIT Press, 2001
• Datteri, E., Tamburrini, G., "Bio-robotic experiments and scientific method", in Magnani, L., Dossena, R. (eds), *Computing, Philosophy and Cognition*, College Publications, London, 2005.