Handbook of Robotics

Chapter 61: Biologically-inspired robots

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Chapter 61

Biologically-inspired Robots

61.1 Introduction

Human inventors and engineers have always found in Nature's products an inexhaustible source of inspiration. About 2400 years ago, for instance, Archytas of Tarentum allegedly built a kind of flying-machine, a wooden pigeon balanced by a weight suspended from a pulley, and set in motion by compressed air escaping from a valve. Likewise, circa 105 AD, the Chinese eunuch Ts'ai Lun is credited with inventing paper, after watching a wasp create its nest. More recently, the architectural design of the still-unfinished Sagra Familia cathedral in Barcelona displays countless borrowings from mineral and vegetal exuberance.

Although a similar tendency underlie all attempts at building automata or proto-robots up to the middle of the last century (Cordeschi, 2002), in the last decades roboticists borrowed much more from mathematics, mechanics, electronics and computer science than from biology. On the one hand, this approach undoubtedly solidified the technical foundations of the discipline and lead to the production of highly successful products, especially in the field of industrial robotics. On the other hand, it served to better appreciate the gap that still separates a robot from an animal, at least when qualities of autonomy and adaptation are sought. As such qualities are required in a continually growing application field -- from planet exploration to domestic uses -- a spectacular reversal of interest towards living creatures can be noticed in current-day robotics, up to the point that it has been said that natural inspiration is the "new wave" of robotics (Paulson, 2004).

Undoubtedly, this new wave would not have been possible without the synergies generated by recent advances in biology -- where so-called integrative approaches now produce a huge amount of data and models directly exploitable by roboticists --, and in technology -- with the massive availability of low-cost and power-efficient computing systems, and with the development of new materials exhibiting new properties. This will be demonstrated in this article that first reviews recent research efforts in bioinspired morphologies, sensors, and actuators. Then, control architecture that, beyond mere reflexes, implement cognitive abilities -- like memory or planning -- or adaptive processes -- like learning, evolution and development -- will be described. Finally, the article will also report related works on energetic autonomy, collective robotics, and biohybrid robots.

It should be noted that this chapter will describe both bioinspired and biomimetic realizations. In fact, these two terms respectively characterize the extremities of a continuum for which, on the one side, engineers seek to reproduce some natural result, but not necessarily the underlying means, while, on the other side, they seek to reproduce both the results and the means. Thus, bioinspired robotics tends to adapt to traditional engineering approaches some principles that are abstracted from the observation of some living creature, whereas biomimetic robotics tends to replace classical engineering solutions by as detailed mechanisms or processes that it is possible to reproduce from the observation of this creature. In practice, any specific application usually lies somewhere between these two extremities. Be that as it may, because biomimetic realizations are always bioinspired, whereas the reverse is not necessarily true, qualifying expressions like bioinspired or biologically-inspired will be preferentially used in this chapter.

61.2 Bio-inspired morphologies

Although not comparable to that of real creatures, the diversity of bioinspired morphologies that may be found in the realm of robotics is nevertheless quite impressive. Actually, a huge number of robots populate terrestrial, as well as aquatic or aerial environments, and look like animals as diverse as dogs, kangaroos, sharks, dragonflies, or jellyfishes, not mentioning humans (Fig 1).

In nature, the morphology of an animal fits its ecology and behavior. In robotics applications, bioinspired morphologies are seldom imposed by functional considerations. Rather, as close a resemblance as possible to a given animal is usually sought per se, as in animatronics applications for entertainment industry. However, several other applications are motivated by the functional objective of facilitating human-robot interactions, thus allowing, for instance, children or elderly people to adopt artificial pets and enjoy their company. Such interactions are facilitated in the case of so-called anthropopathic or human-friendly robots, like Kismet at MIT (Breazeal, 2002) or WE-4RII at Waseda University (Itoh et al., 2006), which are able to perceive and respond to human emotions, and to themselves express apparent emotions influencing their actions and behavior (Fig 2).

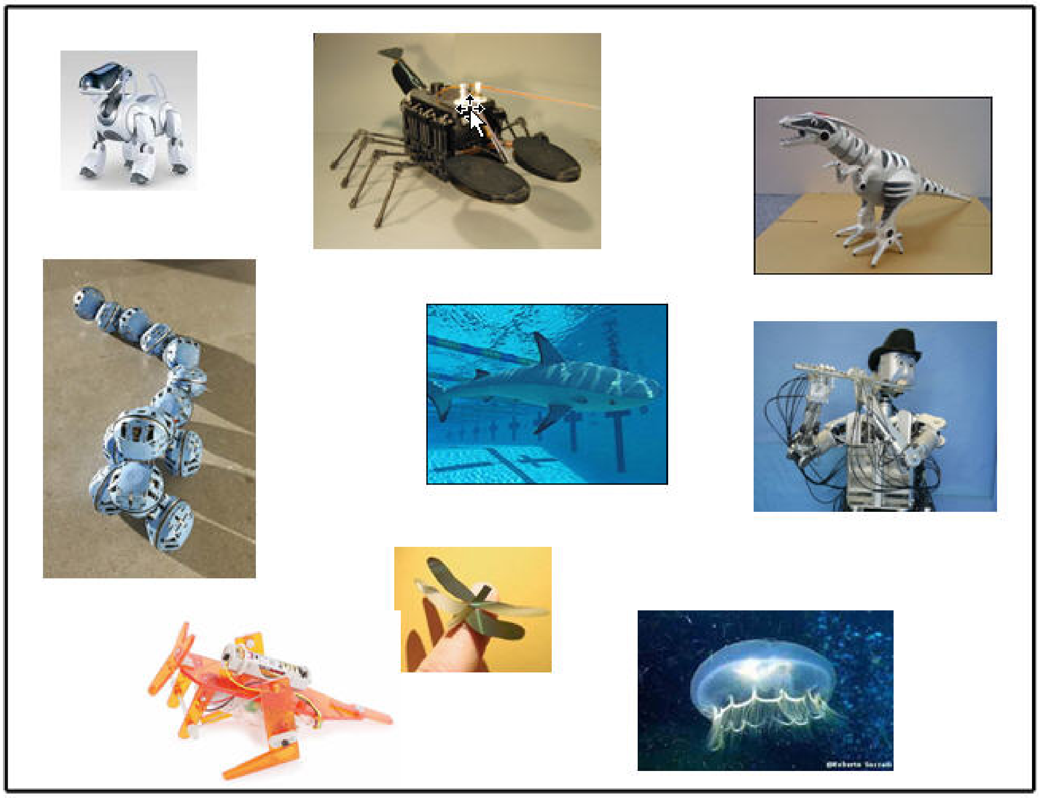


Fig 1. A collection of zoomorphic robots.

Likewise, the Uando robot of Osaka University (MacDorman and Ishiguro, 2006) is controlled by air actuators providing 43 degrees of freedom. The android can make facial expressions, eye, head, and body movements, and gestures with its arms and hands. Touch sensors with sensitivity to variable pressures are mounted under its clothing and silicone skin, while floor sensors and omnidirectional vision sensors serve to recognize where people are in order to make eye contact while addressing them during conversation. Moreover, it can respond to the content and prosody of a human partner by varying what it says and the pitch of its voice (Fig 2). See this Handbook's chapter 59 for more references on human-friendly robots.

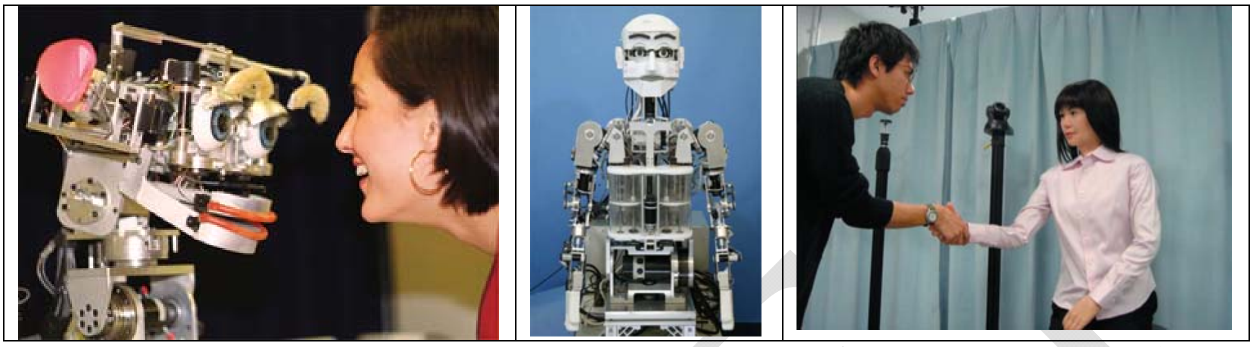


Fig 2. Kismet (Left), WE-4RII (Middle) and Uando (Right) humanoid robots.

Another active research area in which functional considerations play a major role is that of shape-shifting robots that can dynamically reconfigure their morphology according to internal or external circumstances. Biological inspiration stems from organisms that can regrow lost appendages, like the tail in lizards, or from transitions in developmental stages, like morphogenetic changes in batrachians. For instance, the base topology of the Conro self-reconfigurable robot developed in the Polymorphic Robotics Laboratory at USC-ISI is simply connected as in a snake, but the system can reconfigure itself in order to grow a set of legs or other specialized appendages (Fig. 3) thanks to a dedicated hormone-like adaptive communication protocol (Shen et al., 2002).

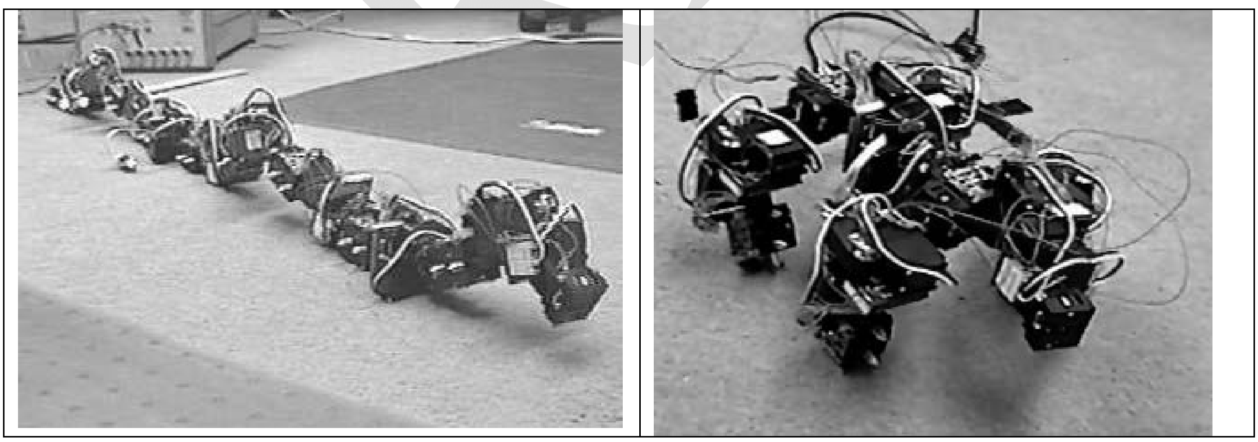


Fig 3. The Conro robot configured as a snake (left) or as a hexapod (right).

Chapter 40 in this Handbook is devoted to distributed and cellular robots and provides other examples of such reconfigurable robots.

61.3 Bio-inspired sensors

61.3.1 Vision

Bio-inspired visual sensors in robotics range from very simple photo sensitive devices that mostly serve to implement phototaxis to complex binocular devices used for more cognitive tasks like object recognition, for instance.

Phototaxis is seldom the focus of dedicated research. It is rather usually implemented to merely force a robot to move and exhibit other capacities, like obstacle-avoidance or inter-robot communication.

Several visual systems calling upon optic-flow monitoring are particularly useful in the context of navigation tasks and are implemented on a variety of robots. This is the case with the work done in Marseilles' Biorobotics Laboratory that serves to understand how the organization of the compound eye of the housefly, and how the neural processing of visual information obtained during the flight, endow this insect with various reflexes mandatory for its survival. The biological knowledge thus acquired was exploited to implement opto-electronic devices allowing a terrestrial robot to wander in its environments while avoiding obstacles (Franceschini et al., 1992), or tethered aerial robots to track a contrasting target (Viollet and Franceschini, 2001) or to automatically perform terrain-following, take-off or landing (Ruffier et al., 2005) (Fig. 4).

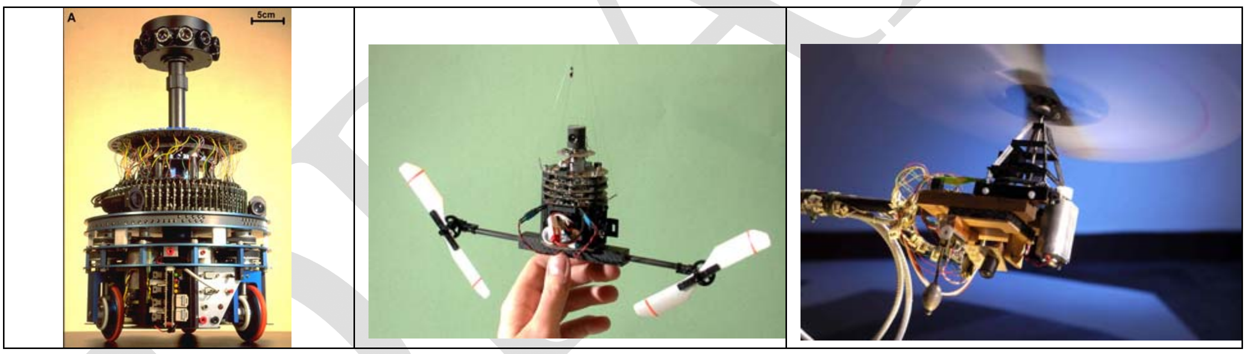


Fig. 4. Opto-electronic devices inspired by the housefly's compound eye. Left : device for obstacle-avoidance capacities. Middle : device for target tracking. Right : device for terrain-following, take-off and landing.

The desert ant *Cataglyphis*, while probably merging optic-flow and odometry monitoring to evaluate its travel distances, is able to use its compound eyes to perceive the polarization pattern of the sky and infer its orientation. This affords it accurate navigation capacities that make it possible to explore its desert habitat for hundreds of meters while foraging, and return back to its nest on an almost straight line, despite the absence of conspicuous landmarks and despite the impossibility of laying pheromones on the ground that would not almost immediately evaporate. Inspired by the insect's navigation system, mechanisms for path integration and visual piloting have been successfully employed on mobile robot navigation in the Sahara desert (Möller et al., 1998).

Among the robotic realizations that are targeted at humanoid vision, some aim at integrating information provided by foveal and peripheral cameras. Ude et al. (2003), in particular, describe a system that uses shape and color to detect and pursue objects through peripheral vision and, then, recognizes the object through a more detailed analysis of higher resolution foveal images. The classification is inferred from a video stream rather than from a single image and, when a desired object is recognized, the robot reaches for it and ignores other objects (Fig. 5). Common alternatives to the use of two cameras per eye consist in using space variant vision and, in particular, log-polar images. As an example, Metta (2001) describes an attentional system that should be extended with modules for object recognition, trajectory tracking, and naïve physics understanding during the natural interaction of the robot with the environment.

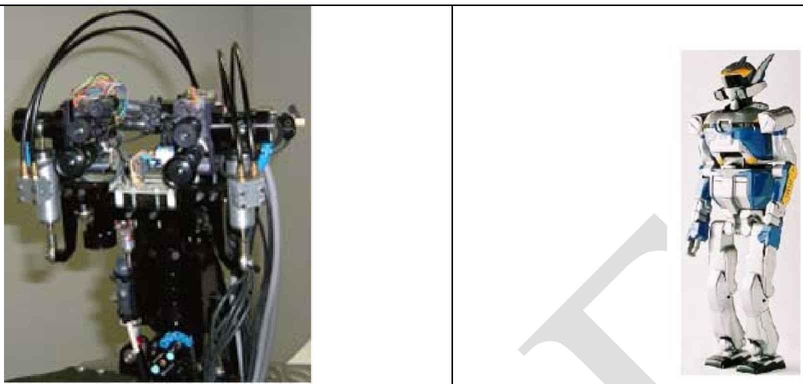


Fig 5. Left: Four cameras implement foveal and peripheral vision in the head of the humanoid robot DB at ATR. Foveal cameras are above peripheral cameras. Right: HRP2 humanoid robot.

Other examples of robotic applications of perceptual processes underlying human vision are provided in this Handbook's chapter 64 on perceptual robotics.

Vision-based SLAM (Simultaneous Localization And Mapping) systems have also been implemented on humanoid robots, with the aim of increasing the autonomy of these machines. In particular, Davison et al. (2005) used the HRP2 robot (Fig. 5) to demonstrate real-time SLAM capacities during agile combinations of walking and turning motions, using the robot's internal inertial sensors to monitor a type of 3D odometry that reduced the local rate of increase in uncertainty within the SLAM map. The authors speculate that the availability of traditional odometry on all of the robot's degrees of freedom will allow more long-term motion constraints to be imposed and exploited by the SLAM algorithm, based on knowledge of possible robot configurations. Additional references to SLAM techniques are to be found in chapter 38 of this Handbook.

As another step towards autonomy in humanoid robots, mapping and planning capacities may be combined. Michel et al. (2005), for instance, demonstrate that a real-time vision-based sensing system and an adaptive footstep planner allow a Honda ASIMO robot to autonomously traverse dynamic environments containing unpredictably moving obstacles.

61.3.2 Audition

Like vision, the sense of hearing in animals as been implemented on several robots to exhibit mere phonotaxis behavior or more complex capacities, such as object-recognition.

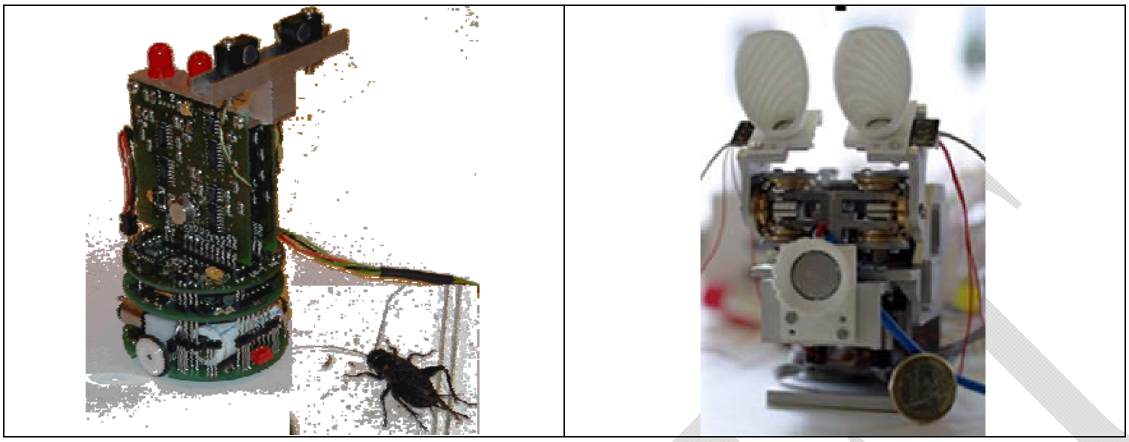


Fig 6. Left: A Khepera robot equipped with a cricket-like auditory system. Right: CIRCE robotic bat head.

At the University of Edinburgh, numerous research efforts are devoted at understanding the sensory-motor pathways and mechanisms that underlie positive or negative phonotaxis behavior in crickets through the implementation of various models on diverse robots such as the Khepera shown on Fig. 6. In particular, an analogue very large scale integrated (aVLSI) circuit modeling the auditory mechanism that serves a female cricket to meet a conspecific male or to evade a bat -- by the calling song or the echolocation calls they respectively produce -- has been built. The corresponding results suggest that the mechanism outputs a directional signal to sounds ahead at calling song frequency and to sounds behind at echolocation frequencies, and that this combination of responses simplifies later neural processing in the cricket (Reeve et al., in press). This processing is the subject of complementary modeling efforts in which spiking neuron controllers are also tested on robots, thus allowing exploring the functionality of identified neurons in the insect, including the possible roles of multiple sensory fibers, mutually inhibitory connections, and brain neurons with pattern-filtering properties. Such robotic implementations also make the investigation of multimodal influences on the behavior possible, via the inclusion of an optomotor stabilization response and the demonstration that it may improve auditory tracking, particularly under conditions of random disturbance (Reeve and Webb, 2003).

Concerning more cognitive capacities, within the framework of the EC (European Community) project CIRCE (Chiroptera Inspired Robotic CEphaloid), a bat head (Fig 6) is used to investigate how the world is not just perceived, but actively explored, by bats. In particular, the work aims at identifying how the various shapes, sizes, and movements influence the signals the animal receives from its environment (Müller and Hallam, 2005). It is hoped that the principles gleaned from such work will prove useful in developing better antennas, particularly for wireless devices that are in motion and need to pick up complex signals from different directions.

Likewise, the Yale Sonar Robot that is modeled after bat and dolphin echolocation behavior is said to be so sensitive that it can tell whether a tossed coin has come up heads or tails. Called Rodolph -- short for Robotic dolphin -- the robot is equipped with electrostatic transducers that can act either as transmitters or receivers to serve as the robot's "mouth" and "ears". The design is inspired by bats, whose ears react by rotating in the direction of an echo source, and by dolphins, which appear to move around in order to place an object at a standard distance, thus reducing the complexity of object recognition (Kuc, 1997). Additional references to bioinspired sonars are to be found in this Handbook’s chapter 21, dedicated to sonar sensing.

Nakadai et al. (2003) describe a system that allows a humanoid robot to listen to a specific sound source under noisy environments -- a human capability that is known as “cocktail party effect” -- and to listen to several speeches simultaneously, thus allowing to cope with situations where someone or something playing sounds interrupts conversation -- a capacity known as “barge-in” in spoken dialog systems. This system calls upon active motions directed at the sound source to improve localization by exploiting an « auditory fovea ». It also capitalizes on audio-visual integration, thus making localization, separation and recognition of three simultaneous speeches possible.

61.3.3 Touch

It is often asserted that, of all the five senses, touch is the most difficult to replicate in mechanical form. Be that as it may, a passive, highly compliant tactile sensor has been designed for the hexapedal running robot Sprawlette at Stanford drawing inspiration by how the cockroach *Periplaneta americana* uses antenna feedback to control its orientation during a rapid wall-following behavior. Results on the stabilization of the robot suggest that the cockroach uses, at least in part, the rate of convergence to the wall -- or “tactile flow” -- to control its body orientation (Cowan et al., 2005). To make it possible to detect the point of greatest strain, or to differentiate between different shapes the sensor is bent into, more advanced versions of the antenna are currently under development (Fig 7).

While a cockroach’s antenna consists of multiple rigid segments and is covered all along its length with sensory receptors, a rat’s whisker consists of a single, flexible, tapered hair and has tactile sensors located only at its base. The way two arrays of such sensors afford capacities of obstacle-avoidance, texture discrimination and object recognition has inspired several robotic realizations, notably that described by Russel and Wijaya (2003) in which the whiskers are passive and rely upon the motion of the robot in order to scan the surface profile of touched objects. The robot is able to recognize a few objects formed from plane, cylindrical and spherical surfaces. By using its simple manipulator, it can pick up and retrieve small objects.

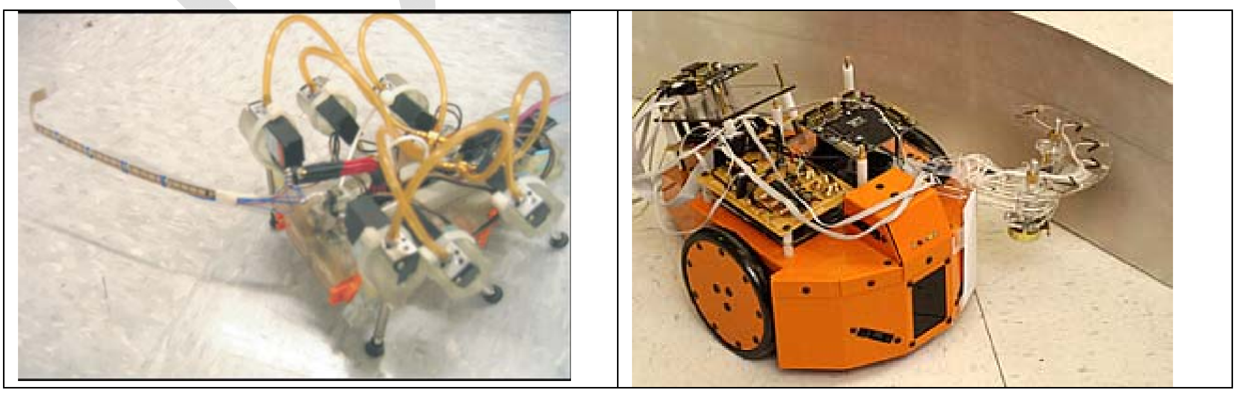


Fig 7. Left: A simple antenna mounted on a Sprawlette robot. Right: a more advanced tactile device.

Conversely, Pearson et al. (2005) describe a touch system based on computational models of whisker-related neural circuitry in the rat brain, in which the whiskers will be actively scanning the surroundings. This work will contribute to the EC project ICEA (Integrating Cognition, Emotion and Autonomy -- http://www2.his.se/icea/) whose primary aim is to develop a cognitive systems architecture integrating cognitive, emotional and bioregulatory (self-maintenance) processes, based on the architecture and physiology of the mammalian brain.

In the field of humanoid robotics, investigations on touch sensors are conducted at the University of Tokyo, where a robotic hand calling upon organic transistors as pressure sensors (Fig 8a) has been produced. The same technology served to make a flexible artificial skin that can sense both pressure and temperature (Fig 8b), thus more closely imitating the human sense of touch (Someya et al., 2005).

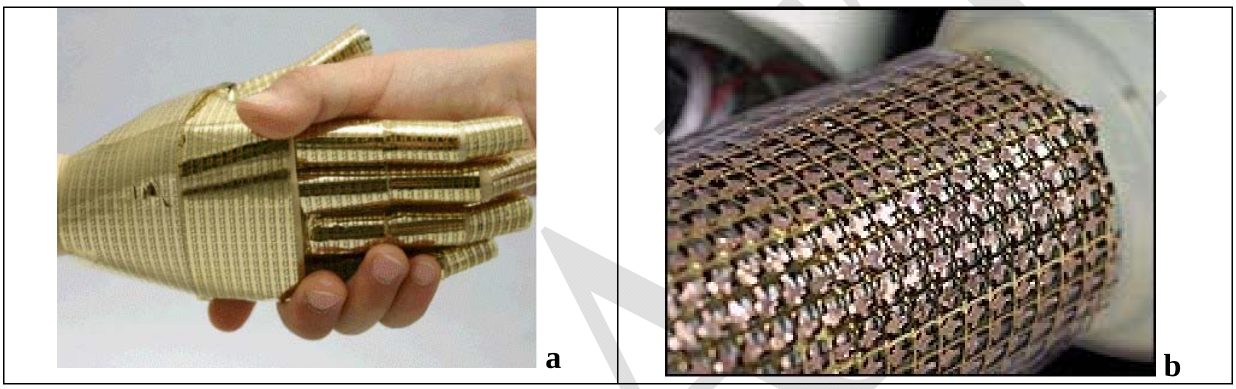


Fig 8. Artificial skin devices at Tokyo University. a) pressure-detection. b) pressure and temperature detection.

Another step in this direction has been made at the University of Nebraska (Maheshwari and Saraf, 2006**)** where a thin-film tactile sensor, which is as sensitive as the human finger in some ways, has been designed. When pressed against a textured object, the film creates a topographical map of the surface, by sending out both an electrical signal and a visual signal that can be read with a small camera. The spatial resolution of these "maps" is as good as that achieved by human touch, as demonstrated by the image obtained when putting a penny on this mechanical fingertip (Fig 9).

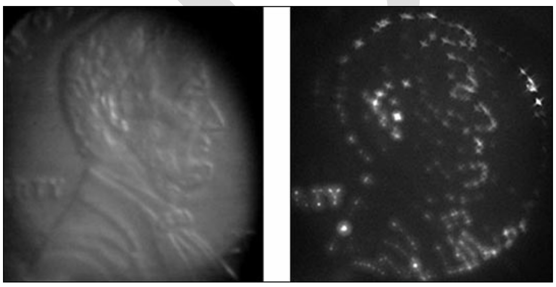


Fig. 9. Left : the optical image of a Lincoln penny. Right : the corresponding pressure image from the tactile sensor.

Although such sensor deals with texture in a way that is not at all like a fingertip, it has a high enough resolution to "feel" single cells, and therefore could help surgeons find the perimeter of a tumor during surgical procedures. Cancer cells -- in particular, breast cancer cells -- have levels of pressure that are different from normal cells, and should feel "harder" to the sensor.

61.3.4 Smell

The way the nematod *Caenorhabditis elegans* uses chemotaxis -- probably the most widespread form of goal-seeking behavior -- to find bacterial food sources by following their odors has been investigated at the University of Oregon. The worm having a small nervous system (302 neurons), whose neurons and connectivity pattern have been completely characterized, the neural circuit controlling chemotaxis is well known and, when implemented on a robot, it proves to be able to cope with environmental variability and noise in sensory inputs (Morse et al., 1998). The long-term objective of such work is to design a cheap, artificial eel that could locate explosive mines at sea. Among the research efforts that tackle the related and highly challenging issue of reproducing the odor plume-tracking behavior in marine animals, recent results obtained on the RoboLobster are put in perspective in Grasso (2001) (Fig 10).

Other bio-inspired systems for odor recognition are under development in several places. For instance, the chest of the humanoid WE-4RII robot of Waseda University (Fig 2) is equipped with two mechanical lungs each consisting of a cylinder and a piston, thanks to which the robot breathes air. Being also equipped with four semiconductor gas sensors, it recognizes the smells of alcohol, ammonia and cigarette smoke (Itoh et al., 2004b).

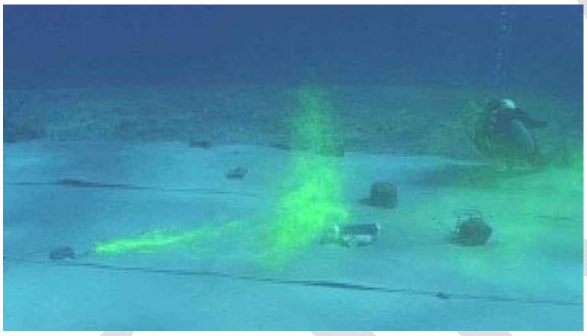


Fig 10. Odor plume-tracking experiments with the RoboLobster of Brooklyn College.

61.3.5 Taste

A first robot with a sense of taste has been recently developed by NEC System Technologies, Ltd. Using infrared spectroscopic technology, this robot is capable of examining the taste of food and giving its name as well as its ingredients. Furthermore, it can give advice on the food and on health issues based on the information gathered. The latest developments afford the robot with capacities of distinguishing good wine from bad wine, and Camembert from Gouda (http://www.necst.co.jp/english/news/20061801/index.htm).

61.3.6 Idiothetic sensors

Whereas the preceding sensors were all providing information about an animal’s or a robot’s external world -- they are called allothetic sensors by biologists -- other sensors may provide information about a creature’s internal state. Although such so-called idiothetic sensors are widespread in robotic applications -- measuring variables like temperature, pressure, voltage, accelerations, etc. -- they are seldom biologically inspired, but in the implementation of a variety of visual-motor routines (smooth-pursuit tracking, saccades, binocular vergence, and vestibular-ocular and opto-kinetic reflexes), like those that are at work in the humanoid Cog robot mentioned later.

61.4 Bio-inspired actuators

61.4.1 Locomotion

- **Crawling**

Because they are able to move in environments inaccessible to humans, such as pipes or collapsed buildings, numerous snake-like robots have been developed for exploration and inspection tasks, as well as for participation to search and rescue missions. The AmphiBot of EPFL (Fig 11) extends the capacities of these robots because it is amphibious and capable of both swimming and lateral undulatory locomotion. Being inspired by central pattern generators (CPG) found in vertebrate spinal cords, it also contributes to better understand how their central nervous system controls movement in animals like snakes and elongate fishes such as lampreys (Crespi et al., 2005).

Other applications are sought within the framework of the EC project BIOLOCH (BIO-mimetic structures for LOComotion in the Human body). In the perspective of helping doctors diagnose disease by carrying tiny cameras through patients' bodies, a robot designed to crawl through the human gut by mimicking the wriggling motion of an undersea worm has been developed by the project partners (Tsakiris et al., 2005). Drawing inspiration from the way polychaetes, or "paddle worms", use tiny paddles on their body segments to push through sand, mud or water, they tackled the issue of supplying traditional forms of robotic locomotion that would not work in the peculiar environment of the gut (Fig 11). The device is expected to lessen the chance of damaging a patient’s internal organs with a colonic endoscope, and to enhance the exploration capacities afforded by “camera pills”.

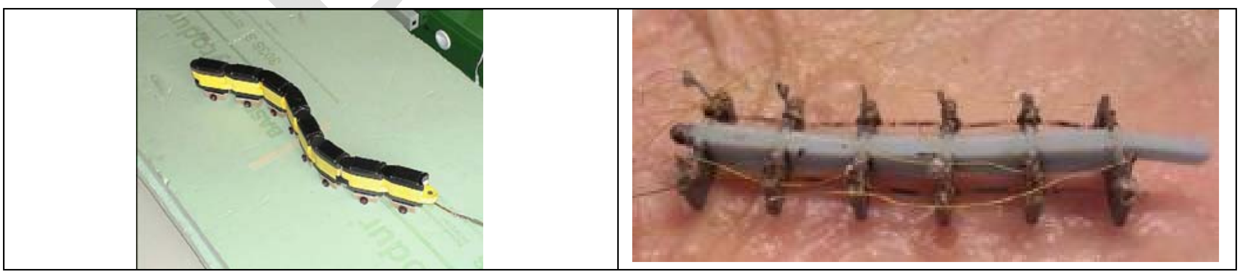


Fig 11. Left: A preliminary version of the AmphiBot (here with passive wheels). Right : A Worm-inspired robot designed to crawl through intestines.

Walking

In the PolyPEDAL (Performance Energetics and Dynamics of Animal Locomotion) Laboratory at Berkeley, general principles about legged locomotion are sought, through the comparison of the sensory-motor equipment and the behavior of a variety of animals. In particular, it has been discovered that many animals self-stabilize to perturbations without a brain or its equivalent because control algorithms are embedded in their physical structure. Shape deposition manufacturing has allowed engineers to tune legs of the SPRAWL family of hand-sized hexapedal robots inspired by the cockroach that are very fast (up to 5 body-lengths per second), robust (hip-height obstacles), and that self-stabilize to perturbations without any active sensing (Clark et al., 2001). One such robot is shown on Fig. 7. A cricket-inspired robot, approximately 8 cm long, designed for both walking and jumping is under development at Case Western Reserve University, and is shown on Fig. 12. McKibben artificial muscles will actuate the legs, compressed air will be generated by an onboard power plant, and a continuous-time recurrent neural network will be used for control. Additionally, front legs will enable climbing over larger obstacles and will also be used to control the pitch of the body before a jump and, therefore, aim the jump for distance or height.

Engineers from Boston Dynamics claim they have developed « the most advanced quadruped robot on Earth » for the US Army. Called BigDog, it walks, runs, climbs on rough terrain, and carries heavy loads. Being the size of a large dog or a small mule, measuring 1 m long, 0.7 m tall and 75 kg weight, BigDog has trotted at 5 km/h, climbed a 35° slope, and carried a 50 kg load so far. BigDog is powered by a gasoline engine that drives a hydraulic actuation system. Its legs are articulated like an animal's, and have compliant elements that absorb shock and recycle energy from one step to the next (Fig 12). Another quadruped with amazing locomotion capabilities is Scout II, presumably the world's first galloping robot, developed at McGill University (Poulakakis et al., 2005). Using a single actuator per leg -- the hip joint providing leg rotation in the sagittal plane -- and each leg having two degrees of freedom (DOF) -- the actuated revolute hip DOF, and the passive linear compliant leg DOF -- the system exhibits passively generated bounding cycles and can stabilize itself without the need of any control action. This feature makes simple open-loop control of complex running behaviors such as bounding and galloping possible.

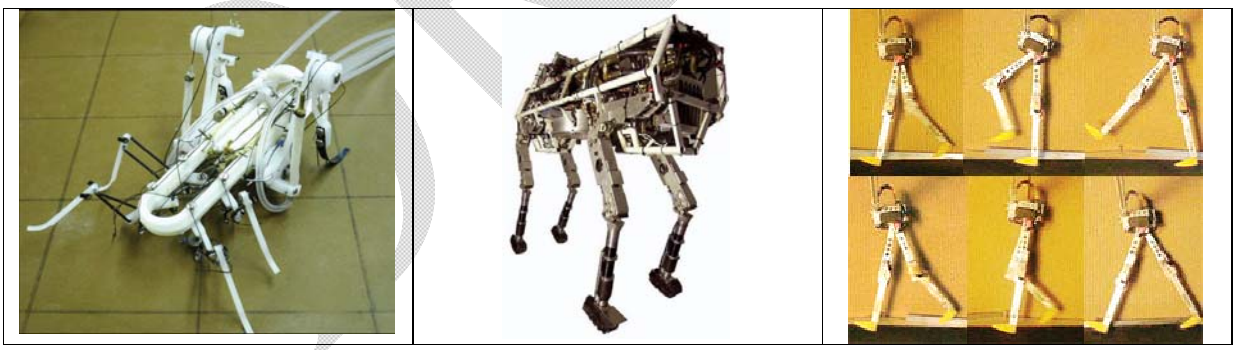


Fig 12. Left: The cricket-robot from Case Western Reserve University. Middle: BigDog from Boston Dynamics. Right: RunBot from Stirling University.

Developed at Stirling University, RunBot is probably the world's fastest biped robot for its size. Being 30 cm high, it can walk at a speed of 3.5 leg-lengths per second, which is comparable to the fastest relative speed of human walking (Fig 12). This robot has some special mechanical features, e.g., small curved feet allowing rolling action and a properly positioned center of mass, that facilitate fast walking through exploitation of its natural dynamics. It also calls upon a sensor-driven controller that is built with biologically inspired sensor and motor-neuron models, the parameters of which being possibly tuned by a policy gradient reinforcement learning algorithm in real-time during walking. The robot does not employ any kind of position or trajectory-tracking control algorithm. Instead, it exploits its own natural dynamics during critical stages of its walking gait cycle (Geng et al., 2006).

Additional references to legged robots are to be found in chapter 16 of this Handbook.

☐ Wall-climbing

In the Biomimetic Dextrous Manipulation Laboratory at Stanford University, researchers are working on a gecko-like robot, called Stickybot, designed to climb smooth surfaces like glass without using suction or adhesives (Fig. 13). Geckos can climb up walls and across ceilings thanks to roughly half a million of tiny hairs, or setae, on the surface of each of their feet and to the hundreds to thousands of tiny pads, or spatulae, at the tip of each hair. Each of these pads is attracted to the wall by intermolecular van der Waals forces, and this allows the gecko's feet to adhere. Conversely, if the hair is levered upward at a 30 degree angle, the spatulae at the end of the hair easily detach. The gecko does this simply by peeling its toes off the surface. Inspired by such structures and mechanisms, the Stickybot's feet are covered with thousands of synthetic setae made of an elastomer. These tiny polymer pads ensure a large area of contact between the feet and the wall, thus maximizing the expression of intermolecular forces. In the same laboratory, a six-legged robot called Spinybot climbs vertical surfaces according to similar principles. Spinybot’s feet and toes are made from several different polymers, which range from flexible to rigid, thus enabling the robot to absorb jolts and bumps, much as animals' feet do (Sangbae, 2005).

The project RiSE (Robots in Scansorial Environments) funded by the DARPA Biodynotics Program constitutes an extension of these research efforts that aims at building a bio-inspired climbing robot with the unique ability to walk on land and climb on trees, fences, walls, as well as other vertical surfaces. It calls upon novel robot kinematics, precision-manufactured compliant feet and appendages, and advanced robot behaviors (Saunders et al., 2006; Spenko et al., 2006) (Fig. 13).

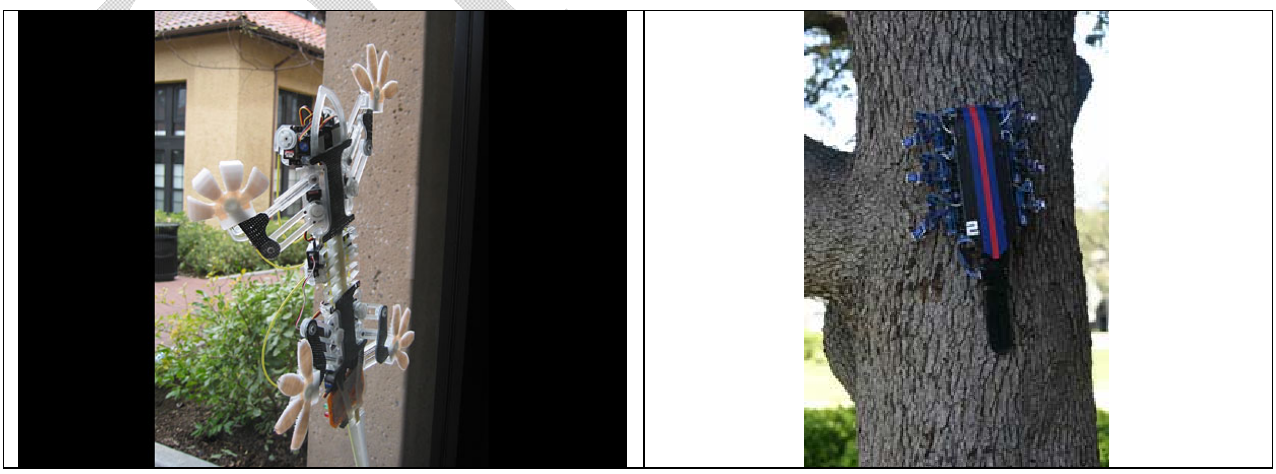


Fig 13. Wall climbing robots at Stanford. Left : Stickybot. Right : RiSE robot.

Jumping

In the perspective of environment exploration and monitoring, Scarfogliero et al (2006) describe a lightweight micro-robot that demonstrates that jumping can be more energetically efficient than just walking or climbing, and which can be used to overcome obstacles and uneven terrains. During the flight phase, energy from an electric micro-motor is collected in the robot's springs, while it is released by a click mechanism during take-off. In this way instant power delivered by rear legs is much higher than the one provided by the motor.

Swimming

Several biomimetic robots are being produced that emulate the propulsive systems of fish, dolphins, or seals, and exploit the complex fluid mechanics these animals use to propel themselves. A primary goal of these projects is to have machines that can maneuver by taking advantage of flows and body positions, leading to huge energy savings, and substantially increasing the length of swimming time. For instance, the group at MIT Towing Tank made two robotic fish, a "robotuna" and a "robopike", that use servo motors and spring element spines (Fig 14), and serve to demonstrate the advantages of flapping foil propulsion. It has thus been shown that RoboTuna can reduce its drag in excess of 70% compared to the same body towed straight and rigid (Barrett et al., 1999). Likewise, it appears that biomimetic fish can turn at a maximum rate of 75 °/s, whereas conventional rigid-bodied robots and submarines turn at approximately 3-5 °/s (Fish, 2006).

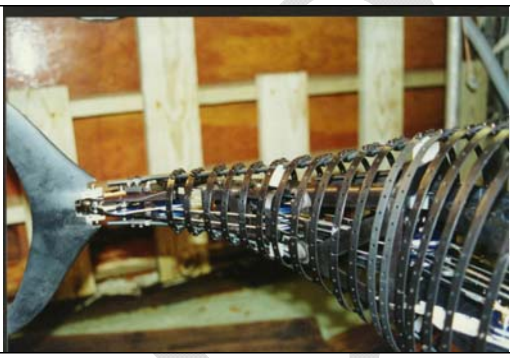


Fig 14. MIT swimming robots. Left: RoboTuna. Right: RoboPike.

The robot Madeleine of Vassar College imitates the design of a turtle. Measuring 80 by 30 cm and weighting 24 kg, it has a comparable power output, and its polyurethane flippers have the same stiffness as a real turtle's, but are operated by electric motors connected to an onboard computer (Fig.15). Because it may swim underwater using four flippers, like many extinct animals, or with two flippers, like modern animals, this robot has been used to test theories of locomotion in existing and extinct animals. It thus appears that having four flippers does not improve the top speed -- apparently because the front flippers created turbulence that interfered with the rear flippers' ability to generate forward propulsion -- but does increase energy use. This may explain why natural selection favored two-flipper animals over four-flipper animals like the plesiosaurs, and why four-flipper animals such as penguins, sea turtles and seals use only two of their limbs for propulsion (Long et al., 2006).

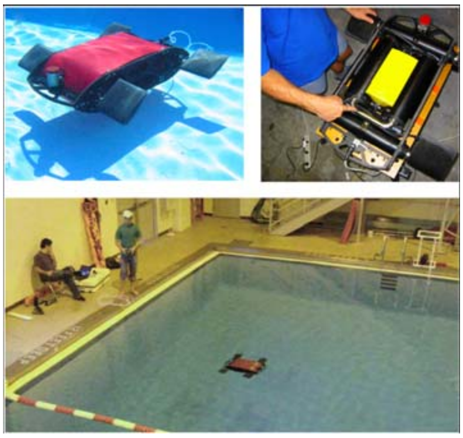


Fig. 15. The robot Madeleine.

- **Flying**

Flapping wings offer several advantages over the fixed wings of today's reconnaissance drones, like flying at low speeds, hovering, making sharp turns and even flying backward. Like in animals, the vortex created beneath each wing is exploited to create the push necessary for robots to take to the sky.

The goal of the Micromechanical Flying Insect (MFI) project at Berkeley is to develop a 25 mm robot capable of sustained autonomous flight, which could be used in search, rescue, monitoring, and reconnaissance. Such tiny robot will be based on biomimetic principles that capture some of the exceptional flight performance achieved by true flies, i.e., large forces generated by non-steady state aerodynamics, a high power-to-weight ratio motor system, and a high speed control system with tightly integrated visual and inertial sensors. Design analysis suggests that piezoelectric actuators and flexible thorax structures can provide the needed power density and wing stroke, and that adequate power can be supplied by lithium batteries charged by solar cells. Likewise, mathematical models capitalizing on wing-thorax dynamics, flapping flight aerodynamics at a low Reynolds number regime, body dynamics, as well as on a biomimetic sensory system consisting of ocelli, halteres, magnetic compass, and optical flow sensors, have been used to generate realistic simulations for MFI and insect flight. In turn, such simulations served to design a flight control algorithm maintaining a stable flight in hovering mode (Deng et al. 2006a,b). A first MFI platform, which flaps its two wings and is the right size, has already been produced (Fig. 16).

The four-winged ornithopter Mentor (Fig. 16), which is developed at the University of Toronto as part of a general research effort targeted at flapping-wing flight (Larijani and DeLaurier, 2002; Mueller and DeLaurier, 2002), is said to be the first artificial device that successfully hovered, doing so with the agility of a hummingbird. In particular, it exhibited the "clap-fling" behavior that the animal uses to draw in air by clapping its wings together, then flinging them apart at high speeds. This creates lift by hurling regions of high pressure below and behind. Likewise, the way it elegantly shifts from hovering to horizontal flight inspires current research. Mentor is about 30 cm long and weights about 0.5 kg, but engineers hope to eventually shrink it to hummingbird size and weight. Other comparable MAV (Micro Aerial Vehicle) devices are reported in Jones et al. (2003, 2004).

Fig 16. MFI (Left) and Mentor (Right) flapping-wing robots.

On a much larger scale, a few manned flapping-wing robots have also been designed. In Votkinsk in the 90's, Toporov built a biplane tow-launched ornithopter that reportedly could be made to climb and fly for 200 m as a result of the pilot's muscular effort (http://www.ornithopter.org/flappingwings/toporov2.htm). More recently, within the Ornithopter project of SRI International and University of Toronto (http://www.ornithopter.ca/index_e.html), the two-winged Flapper plane has flown for 14 sec at an average speed of 88 km/h. It has a 12 m wingspan and weighs 350 kg with pilot and fuel. The wings are made of carbon fiber and Kevlar, and are moved by a gas-powered engine (Fig. 17). A description of previous attempts at making such platform fly is available in DeLaurier (1999).

Finally, despite general skepticism, there are plans for commercial applications of flapping-wing flight, and a prototype with 16 wings and 125 seats is announced to be under development at JCR Technology Corporation (http://www.jcrtechnology.com/) (Fig. 17).

Fig 17. Left: The Flapper plane. Right: JCR Technology's model of a commercial plane.

61.4.2 Grasping

When hunting and grabbing food, the octopus uses all the flexibility its arms are capable of. But, when feeding, the animal is able to bend its flexible arms to form "joints" like those in human arms. Inspired by such dexterous appendages found in cephalopods -- particularly the arms and suckers of octopus, and the arms and tentacles of squid -- Walker et al. (2005) describe recent results in the development of a new class of soft, continuous backbone robot manipulators. Fed by fundamental research into the manipulation tactics, sensory biology, and neural control of octopuses, the work in turn leads to the development of artificial devices based on both electro-active polymers and pneumatic McKibben muscles, as well as to novel approaches to motion planning and operator interfaces for the so-called OCTARM robot (Fig 18). Likewise, inspired by biological trunks and tentacles, a multi-section continuum robot, Air-Octor, in which the extension of each section can be independently controlled, exhibits both bending and extension capacities, and demonstrates superior performance arising from the additional degrees of freedom than arms with comparable total degrees of freedom (Walker et al., 2006) (Fig. 18).

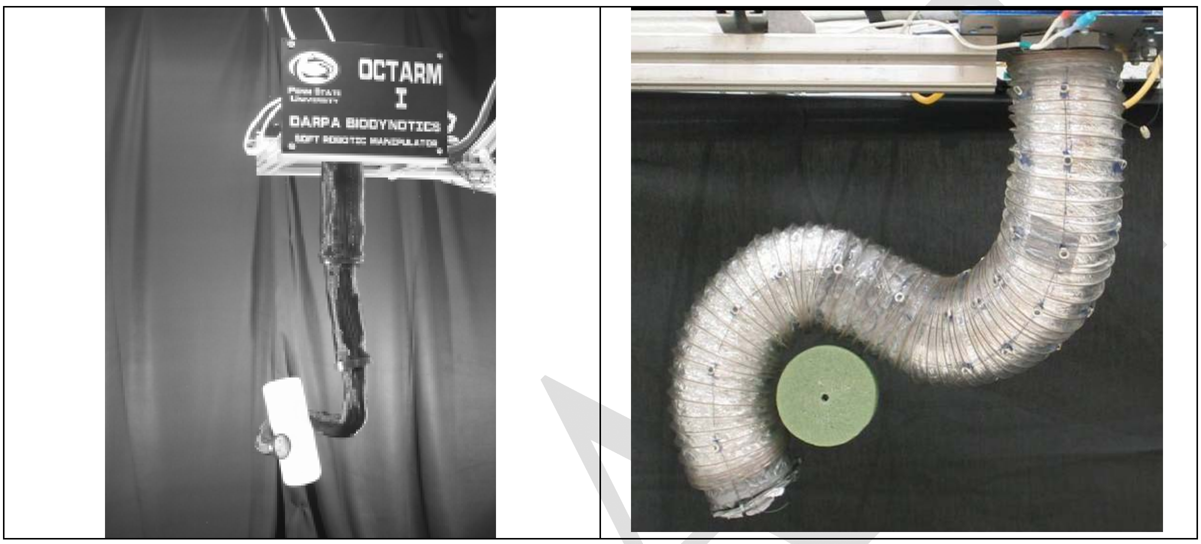
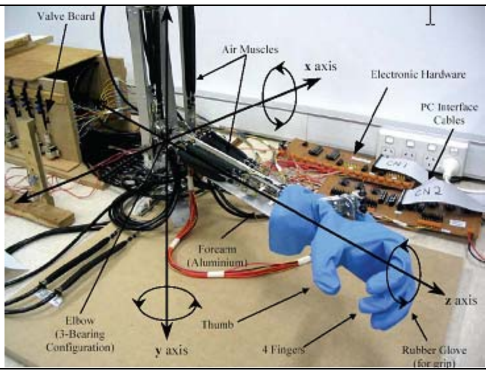


Fig 18. The OCTARM (Left) and Air-Octor (Right) manipulators.

Human grasping has inspired the humanoid hand developed at Curtin University of Technology by Scarfe and Lindsay (2006). The corresponding system presents 10 individually controllable degrees of freedom ranging from the elbow to the fingers, and is actuated through 20 McKibben air muscles each supplied by a pneumatic pressure-balancing valve that allows for proportional control to be achieved with simple and inexpensive components. The hand is able to perform a number of human-equivalent tasks, such as grasping and relocating objects (Fig 19). A similar research is funded by the EC CYBERHAND project that aims at developing a cybernetic prosthetic hand (Carozza et al., 2003). It is hoped that the device will re-create the "life-like" perception of the natural hand, and thus increase its acceptability. To this end, biomimetic sensors replicating the natural sensors are to be developed, and dedicated electrodes -- capable of delivering sensory feedback to the amputee’s central nervous system and extracting his intentions -- are to be designed (Fig. 19).

Chapter 15 in this Handbook provides additional references to robot hands.



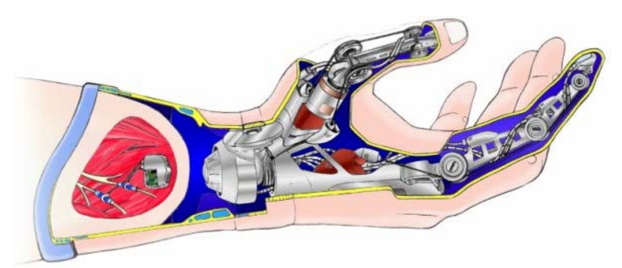


Fig. 19. Left: The humanoid hand of Curtin University of Technology. Right: The CYBERHAND project.

61.4.3 Drilling

Due to ultraviolet flux in the surface layers of most solar bodies, future astrobiological research is increasingly seeking to conduct subsurface penetration and drilling to detect chemical signature for extant or extinct life. To address this issue, Gao et al. (2005) present a bio-inspired micro-penetrator implementing a novel concept of two-valve-reciprocating motion that is inspired by the way a wood wasp uses its ovipositor to drill holes into trees in order to lay its eggs. Indeed, such ovipositor can be split into two longitudinal halves, one side being equipped with cutting teeth and the other with pockets that serve to carry the sawdust away from the hole. The cutting teeth are used to cut the wood in compression and avoid buckling. The sawdust they produce is deposited into the pockets and carried to the surface on the upstroke. The two sides repeat this process in a reciprocating motion. The corresponding artificial system is lightweight (0.5 kg), driven at low power (3 W), and able to drill deep (1-2 m).

61.5 Bio-inspired control architectures

Attempts at tackling the “whole iguana” challenge (Dennett, 1978) -- i.e., that of integrating sensors, actuators and control in the design of a simple but complete artificial animal -- are abundant in the literature and several above-mentioned realizations come under this objective. However, the corresponding controllers usually implement mere reflexes that serve to cope with present circumstances only. In this paragraph, more cognitive architectures, able to deal with past and future events as well, and in which adaptive mechanisms like learning, evolution and development may be incorporated, will be mentioned.

61.5.1 Behavior-based robotics

Under the aegis of so-called behavior-based robotics -- to which chapter 39 of this Handbook is dedicated -- many systems with minimally-cognitive architectures have been developed. For instance, the series of robots designed by Brooks and his students at MIT demonstrate that the “subsumption architecture” (Brooks, 1986) may endow artificial animals with adaptive capacities that do not necessitate high-level reasoning (Brooks, 1999). Moreover, there are some indications that such control architecture may be at work in real animals, like the coastal snail *Littorina* for example (Connell, 1990). Likewise, the “schemas” that are used by Arkin and his students at the

Georgia Institute of Technology to control numerous other robots (Arkin, 1998) have roots in psychology (Piaget, 1971) and neuroscience (Arbib, 1995).

61.5.2 Learning robots

Different bioinspired learning mechanisms -- like those implementing associative, reinforcement or imitation learning schemes -- are currently at work in robotic applications.

For instance, in the robotics laboratory at Nagoya University, the robot Brachiator is able to swing from handhold to handhold like a gibbon (Fig. 20). The robot is equipped with legs that generate initial momentum, and with a computer vision system to figure out where to place its handlike grippers. A standard reinforcement learning algorithm is used to learn the right sensory-motor coordination required to move along a horizontal scale while hanging on successive rungs: it provides a punishment signal when the robot misses the next handhole, and a reward signal when it succeeds. Thus, after a number of failed trials, the robot eventually succeeds to safely move from one extremity of the scale to the other (Saito and Fukuda, 1996).

Bioinspired associative learning mechanisms are used in applications that capitalize upon the place cells and head-direction cells found in hippocampal and para-hippocampal structures in the brain to implement map-building, localization and navigation capacities in robots (see Filliat and Meyer, 2003; Meyer and Filliat, 2003; Trullier at al., 1997 for reviews). Likewise, reinforcement learning mechanisms inspired by the presumed function of dopaminergic neurons (Khamassi et al., 2005) may be associated with models based on the anatomy and physiology of basal ganglia and related structures (Montez-Gonzalez et al., 2000; Girard et al., 2005), which endow a robot with a motivational system and action-selection capacities -- i.e., those of deciding when to shift from one activity to another, according to the various sub-goals the surprises encountered during the fulfillment of a given mission generate. Such controllers and capacities are currently combined in the Psikharpax artificial rat -- that will be able to explore an unknown environment, to build a topological map of it, and to plan trajectories to places where it will fulfill various internal needs, like “eating”, “resting”, “exploring” or “avoiding danger” (Meyer et al., 2005) (Fig. 20) -- as a contribution to the EC project ICEA mentioned before.

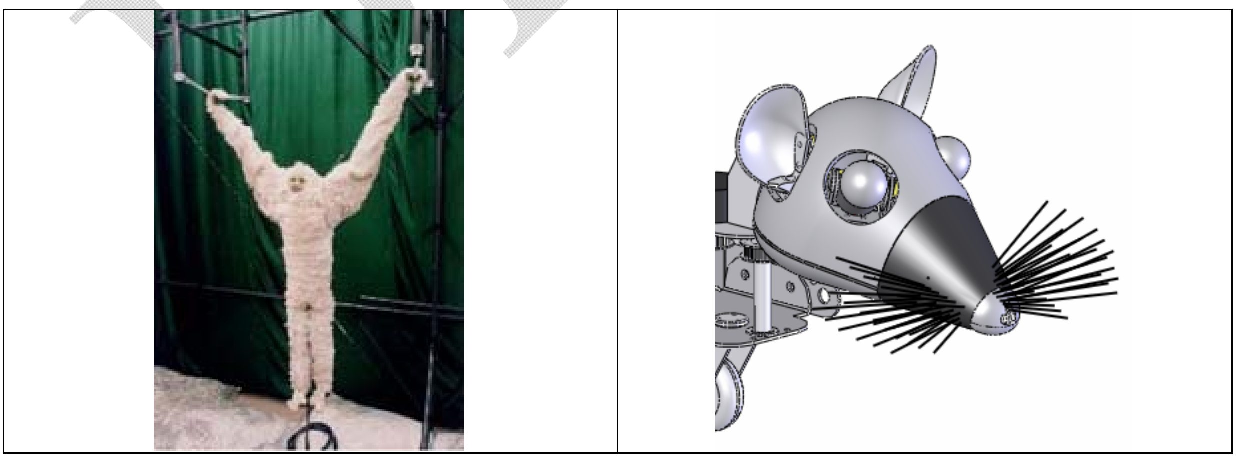


Fig. 20. Left: The Brachiator robot. Right: CAD design of Psikharpax’s head.

MirrorBot, another EC project (http://www.his.sunderland.ac.uk/mirrorbot/), capitalizes on the discovery of mirror neurons in the frontal lobes of monkeys, and on their potential relevance to human brain evolution. Indeed, mirror neuron areas correspond to cortical areas which are related to human language centers, and it seems that these neurons have a critical role in cortical networks establishing links between perception, action and language (Rizzolatti and Craighero, 2004). The project has developed an approach of biomimetic multimodal learning, including imitation learning, using a mirror-neuron-based robot, and has investigated the task of foraging for objects that are designed by their names (Wermter et al., 2005).

At the Neuroscience Institute in San Diego, a series of brain-based devices (BBDs) -- i.e. physical devices with simulated nervous systems that guide behavior, to serve as a heuristic for understanding brain function -- have been constructed. These BBDs are based on biological principles and alter their behavior to the environment through self-learning. The resulting systems autonomously generalize signals from the environment into perceptual categories and through adaptive behavior become increasingly successful in coping with the environment. Among these devices, the robot Darwin VII is equipped with a CCD camera for vision, microphones for hearing, conductivity sensors for taste, and effectors to move its base and its head, and with a gripping manipulator having one degree-of-freedom. Its control architecture is made of 20,000 brain cells, and it is endowed with a few instincts, like an interest in bright objects, a predilection for tasting things, and an innate notion of what tastes good. Thus, the robot explores its environment and quickly learns that striped blocks are yummy and that spotted ones taste bad. Based on the same robotic platform, Darwin VIII is equipped with a simulated nervous system containing 28 neural areas, 53,450 neuronal units, and approximately 1.7 million synaptic connections. It demonstrates that different brain areas and modalities can yield a coherent perceptual response in the absence of any superordinate control, thus solving the so-called binding problem. In particular, the robot binds features such as colors and line segments into objects and discriminates between these objects in a visual scene (Krichmar and Edelman, 2003). Darwin IX is a mobile physical device equipped with artificial whiskers and a neural simulation based on the rat somatosensory system. Neuronal units with time-lagged response properties, together with the selective modulation of neural connection strengths, provide a plausible neural mechanism for the spatiotemporal transformations of sensory input necessary for both texture discrimination and selective conditioning to textures. Having an innate tendency to avoid ‘foot-shock’ pads made of reflective construction paper deposited on the ground of its experimental arena, the robot may be conditioned to avoid specific textures encountered near these aversive stimuli (Seth et al., 2004). Darwin X incorporates a large-scale simulation of the hippocampus and surrounding areas, thus making it possible to solve a dry version of the Morris “water-maze” task, in which the robot must find a hidden platform in its environment using only visual landmarks and self-movement cues to navigate to the platform from any starting position (Krichmar et al., 2005). Besides its ability to learn to run mazes like rats, Darwin X has been thrown in a soccer match, and turned out to be victorious in the 2005 RoboCup U.S. Open. Finally, Darwin XI combines the main characteristics of several previous versions, including a whisker system, and serves to demonstrate the robot’s capacity to learn the reward structure of the environment, as well as the reversal of behavior when this structure changes (http://www.idiap.ch/~rchava/sab06wk/talks.html).

In the perspective of exploring the role that chaotic dynamics may play in self-organizing behavior, researchers involved in the CICT-funded SODAS (Self-Organizing Dynamically Adaptable Systems) project are using a nonlinear dynamics approach to model how the brain -- which is usually in a high-dimensional, disorderly “basal” state -- instantly shifts from a chaotic state to an attractor four or five times a second in order to recognize something familiar, or to make a decision. Such phase transitions and attractors in one area of the brain affect attractors in other areas, and are considered to produce intentional behavior. Focused on the way the brain orients the body in space and uses positive and negative reinforcement from the environment to autonomously navigate to a destination, the goal of the SODAS project is to enable robots to do the same on future NASA missions. In particular, it has produced the KIV architecture that models the brain's limbic system, the simplest neurological structure capable of acting intentionally in an inherently self-consistent manner. Kozma et al. (2005) describe how, in a 2D computer simulation of a Martian landscape, KIV uses positive and negative reinforcement to learn the most effective path to a goal, and uses habituation to reduce the distraction of ambient noise and other irrelevant sensory inputs.

Other bioinspired approaches to the design of control architectures are to be found in this Handbook's chapter 63 dedicated to neurorobotics.

61.5.3 Evolving robots

Using appropriate evolutionary algorithms and artificial selection processes to adapt from generation to generation the code that describes a robot's controller has become current practice. Usually, an efficient code is sought in simulation and then implemented on a real robot (Nolfi and Floreano, 2000).

Fig 21. Left: The robot Elvis. Right: The robot SECT.

At Chalmers University of Technology, for example, such an approach has been used to coordinate the visual information acquired through the two eyes of the humanoid robot Elvis (Fig 21) with the motor orders sent to its effectors. Thus the robot is able to track and point a visual target (Langdon and Nordin, 2001). In a similar manner, at Paris VI University, an incremental approach capitalizing upon solutions to simpler problems to devise solutions to more complex ones has been applied to the evolution of neural controllers for locomotion and obstacle-avoidance in a 6-legged SECT robot (Fig. 21) (Filliat et al., 1999). In the same place, artificial evolution has been applied in simulation to the control of horizontal flight in an artificial bird, or to slope-soaring in a glider (Barate et al., 2006). The corresponding controllers will be implemented on real platforms as a contribution to the Robur project (Doncieux et al., in press).

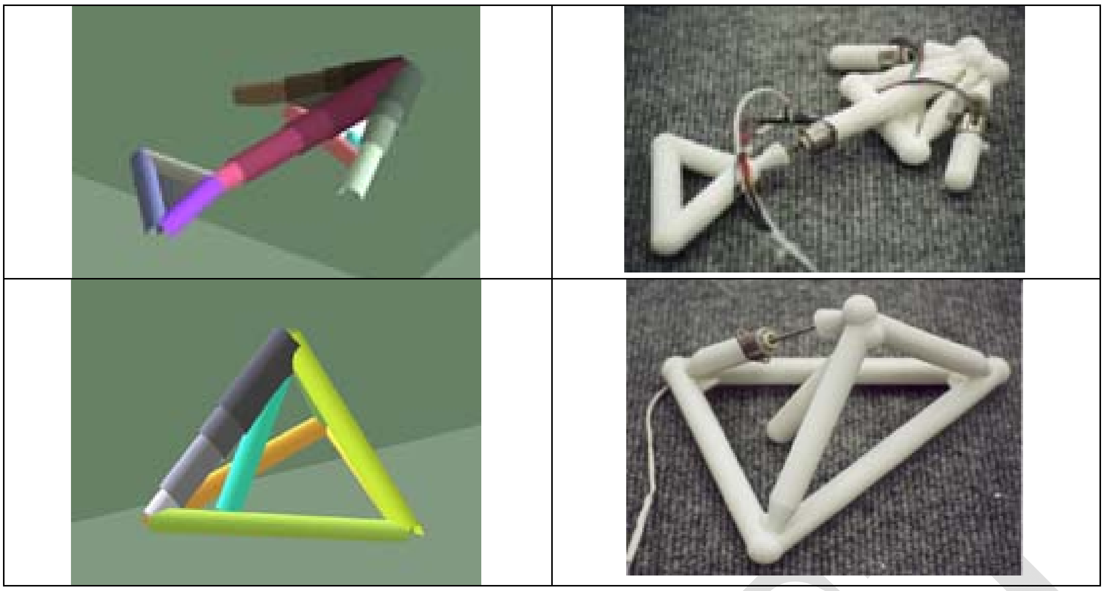


Fig 22. Left : Simple robots whose morphology and control were evolved in simulation. Right : The corresponding physical realizations obtained through rapid-prototyping technology.

For the Golem project (Genetically Organized Lifelike Electro Mechanics) at Brandeis University, Lipson and Pollack (2000) went beyond evolution of hardware controllers and demonstrated for the first time a path that allows transfer of virtual diversity of morphology into reality. They thus conducted a set of experiments in which simple electro-mechanical systems composed of thermoplastic, linear actuators and neurons evolved from scratch to yield physical locomoting machines (Fig. 22).

Additional references to evolutionary robotics are to be found in chapter 62 of this Handbook.

61.5.4 Developing robots

Two varieties of developmental processes are currently applied to robotics. The first one is related to evolution and aims at designing indirect coding schemes which, instead of directly specifying a robot’s behavior and/or shape, describe developmental rules according to which complex neural controllers and/or morphologies can be derived from simple programs (see Kodjabachian and Meyer, 1995 for a review). This is done in the hope that the approach will scale up with the complexity of the control problems to be solved. Such methodology has been applied at Paris VI University to evolve neural controllers for diverse rolling, walking, swimming and flying animats or robots (Meyer et al., 2002).

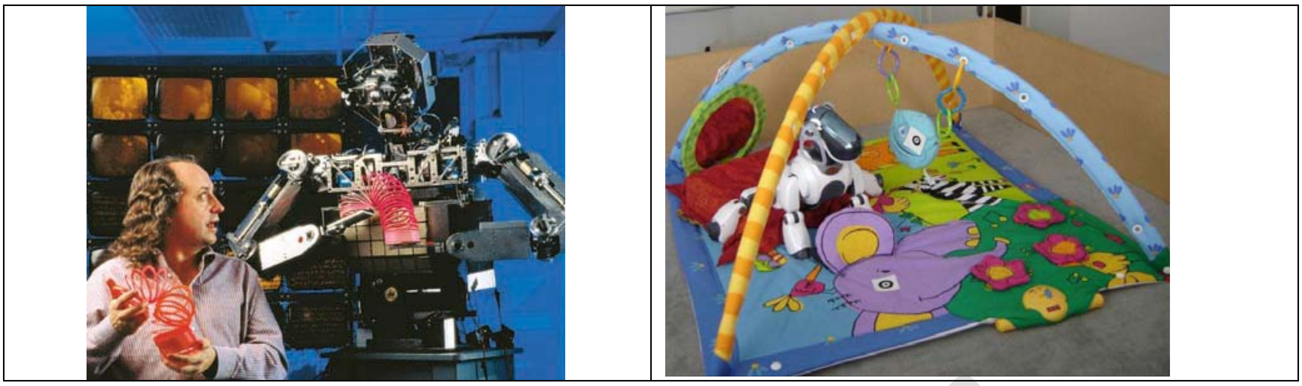


Fig 23. Left: R. Brooks and the Cog robot. Right: An Aibo robot in a playground environment.

The second series of developmental process (see Lungarella et al., 2003 for a review) are related to learning and aim at reproducing the successive sensory-motor and cognitive stages exhibited by developing animals, especially children (Piaget, 1990). As an example of such endeavor, the upper-torso humanoid robot called Cog (Fig. 23) developed at MIT has 22 DOFs and a variety of allothetic and idiothetic sensory systems -- including visual, auditory, vestibular, kinesthetic, and tactile senses (Brooks et al., 1999). It has been endowed with various basic drives provided by its primary designers and, like a human baby, it has gone through a series of parallel developmental stages in its sensory-motor and cognitive capabilities. Among results already acquired, there is the development of mechanisms for reaching and grasping, for rhythmic movement control, for visual search and attention, for imitation learning, for emotional regulation of social dynamics, for saliency identification through shared attention, and for the emergence of a theory of mind[1] (Adams et al., 2000). In a similar perspective, at Sony CSL in Paris, a mechanism of so-called Intelligent Adaptive Curiosity serves as a source of self-development for an Aibo robot placed in a playground environment (Fig 23) and trying to maximize its learning progress. According to this mechanism, the robot focuses on situations which are neither too predictable nor too unpredictable, and the complexity of its activity autonomously increases with time. In particular, it first spends time in situations which are easy to learn, then shifts progressively its attention to situations of increasing difficulty, avoiding situations in which nothing new can be learned (Oudeyer et al., 2005).

61.6 Energetic autonomy

The majority of bio-inspired systems described so far were targeted at increasing the robots' behavioral autonomy. However, a second, even more challenging, issue remains to be tackled, that of reproducing the energetic autonomy of animals, and the way they manage to discover and exploit resources supplying their energy needs.

Very few attempts have still been made in this direction. As a notable exception, Chew Chew was a 12-wheeled, 1 m long, train-like robot developed at the University of South Florida, which derived power through a microbial fuel cell (MFC) stomach (Fig. 24). The stomach broke down food using *Escherichia coli* bacteria and then converted the chemical energy from that digestion process into electricity. The microbes from the bacteria decomposed the carbohydrates supplied by

[1] The expression "theory of mind" is commonly used to design the set of cognitive skills that allow us to attribute beliefs, goals, and desires to other individuals.

the food, which released electrons. These electrons, in turn, supplied a charge to the battery through a reduction and oxidation reaction. The system was very similar to how blood supply and respiration works in humans, but MFC produced electrons rather than oxygen. Being fed by sugar cubes, which were completely dissolved by the microbes, the system produced very little waste (Wilkinson, 2000).

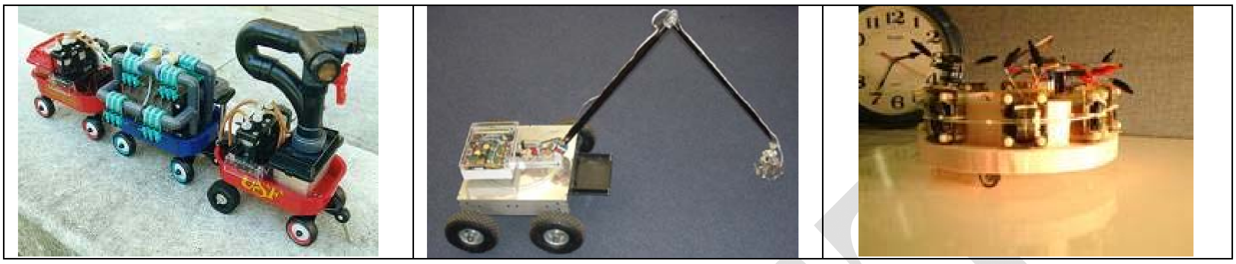


Fig 24. Towards energetically autonomous robots. Left: Chew Chew. Middle: Slugbot. Right: EcoBot-II.

Slugbot (Fig 24) was a robotic slug catcher developed at the University of West England that was equipped with a long articulated arm at the end of which the camera used for detecting slugs, and the gripper used for catching them, were both located. The robot shined red light on the ground and used the camera to identify a shiny, sluglike object which it picked up and dropped in a hopper. Again, a MFC was used to convert the slug biomass to electricity, thus providing the robot's energy supply (Kelly, 2003).

Although praiseworthy, these attempts did not supply enough electricity to generate useful work and they have been abandoned. However, EcoBot-II, a new robot that gets closer to true energetic autonomy, is under development at the University of West England and benefits from previous experience. EcoBot II is equipped with an array of eight MFCs, in the anodes of which bacteria found in sludge act as catalysts to generate energy from dead flies supplied by a human operator or, more precisely, from sugar contained in their exoskeleton. Later on, the robot will be made predatory, using sewage or a pheromone as a bait to catch the flies, and some form of pump to suck them into the digestion chambers. In the MFCs' cathodes, O_2 from free air acts as the oxidizing agent to take up the electrons and protons to produce H_2O. This closes the circuit and keeps the system balanced (Fig. 24). Right now, EcoBot II can crawl along at a top speed of about 2 to 4 cm every 15 minutes and gets enough power to perform phototaxis while remotely reporting temperature measurements at the same time (Ieropoulos et al., 2005). These research efforts contribute to the EC project ICEA already mentioned.

61.7 Collective robotics

Numerous research efforts contribute to the field of bio-inspired collective robotics (Kube et al., 2004) and several of them are described in chapter 41 of this Handbook which is devoted to multiple mobile robot systems. Indeed, the collaboration of two or more workers is mandatory as soon as a given task cannot be accomplished by a single individual. This is the case, for instance, in several species of ants when workers cooperate to retrieve large preys. When one ant finds a prey item, it usually tries to move it, and, when unsuccessful for some time, recruits nestmates through direct contact or chemical marking. Within the group thus formed, ants change position and alignment until the prey can be moved toward the nest. A robotic implementation of this phenomenon is described in Kube and Bonabeau (2000) and illustrates how decentralized problem-solving may be implemented in a group of robots. Other demonstrations of robots that collaborate to solve a given task were produced within the framework of the SWARM-BOTS project that was funded by the EC and was focused on the design and implementation of self-organizing and self-assembling biologically-inspired robots. A swarm-bot is an aggregate of s-bots (mobile robots able to self-assemble by connecting/disconnecting from each other) that can explore, navigate and transport heavy objects on rough terrains in situations in which a single s-bot would have major problems to achieve the task alone, like collectively passing a gap too big for a single robot (Fig. 25) (Mondada et al., 2004).

Fig. 25. Left: A swarm-bot passing a gap. Right: R. Michelson and an Entomopter prototype.

The coordination of a swarm of underwater glider robots in Monterey Bay is at the core of the Adaptive Sampling and Prediction (ASAP) program, which is funded by the Office of Naval Research, and aims at measuring physico-chemical parameters, and at tracking currents and upwellings (Paley et al., in press). Ultimately, the project may lead to the development of robot fleets that forecast ocean conditions and better protect endangered marine animals, track oil spills, and guide military operations at sea. Inspired by the behavior of schools of fish, the coordination policy of the robots allows them to capture the dynamic nature of the ocean while staying in organized patterns even as they are buffeted by strong currents. In particular, the paths that they follow are optimized as the ocean changes so as the measurements they take are permanently as information-rich as possible.

The NASA Institute for Advanced Concepts in Atlanta supports a project aiming at coordinating a fleet of refuelable Entomopter robots deployed from their "mothership," a Pathfinder-like rover, and flapping smartly through the thin, carbon dioxide-laden atmosphere of Mars. With a 1 m wing span, each such robot could haul up to 15 kg of payload. A chemical muscle would generate autonomic wing beating from a liquid fuel source and provide a small amount of electricity to run onboard systems. Waste gas produced by the chemical muscle would be tapped for steering the robot through the air and to run a small navigation gear making obstacle-avoidance possible. Once airborne, the mini-robots would flap at low altitude over Mars, sniffing in atmospheric samples, looking for minerals, and even collecting rock and soil specimens. They could also provide the rover with essential navigation instructions. Finally, returning to home base, the Entomopters would suckle up to the rover, refueling themselves for another round of aerial maneuvers. Mini-prototypes of such a flying robot have already been produced (Michelson, 2002, 2004) (Fig. 26). In the same overall perspective, Huntsberger (2001) describes the map-making memory and action-selection mechanism of BISMARC (Biologically Inspired System for Map-based Autonomous Rover Control), an integrated control system for long duration missions involving robots performing cooperative tasks, which is currently under development at the Jet Propulsion Laboratory in Pasadena.

Besides cooperation, another variety of interaction is put at work in experiments that involve robots in artificial ecosystems, in which they usually compete for the acquisition of spare resources. This is, for example, the case with the Cyber Rodent project at the Okinawa Institute of Science and Technology, a project that seeks to understand the origins of our reward and affective systems by building artificial agents that share the same intrinsic constraints as animals, i.e., self-preservation and self-reproduction. A Cyber Rodent is a robot that can search for and recharge from battery packs on the floor (Fig. 26). It can also “mate” with a nearby agent, a process that entails the transfer of control programs through the robots’ infrared communication ports. In particular, Cyber Rodents are used to study how evolution can help in the learning of battery-capturing behaviors, through the transfer of “genes” coding learning parameters such as the speed of memory update and the width of random exploration (Doya and Uribe, 2005).

Fig. 26. Left: Cyber Rodents seeking battery packs. Right: Three SONY AIBOs paying attention to an object and possibly agreeing on a common word designating it.

Finally, communication is at the heart of several projects that have been undertaken in the line of the so-called Talking Heads experiments (Steels, 2003) that studied the evolution of a shared lexicon in a population of embodied software agents. The agents developed their vocabulary by observing a scene through digital cameras and communicating about what they had seen together (Fig. 26). Among such research efforts, the ECAgents project, which is sponsored by the EC**,** develops a new generation of embodied agents that are able to interact directly with the physical world and to communicate between them and with other agents, including humans. For example, Hafner and Kaplan (2005) studied how non-verbal communication in robots, like pointing gestures, can serve to bootstrap their shared communication systems by influencing the attention of one another. More generally, the ECAgents project investigates basic properties of different communication systems, from simple communication systems in animals to human language and technology-supported human communication, to clarify the nature of existing communications systems and to provide ideas for designing new technologies based on collections of embodied and communicating devices. This will be achieved through the development of new design principles, algorithms, and mechanisms that can extend the functionality of existing technological artefacts (mobile phone, WI-FI devices, robots and robot-like artefacts, etc.) or lead to the development of entirely new ones.

61.8 Biohybrid robots

The solutions that nature has evolved to difficult engineering problems are, in many cases, far beyond present-day engineering capability. Therefore, when engineers are unable to reproduce the functionalities of some sensor, actuator or controller embodied in a living creature, they may try to integrate the corresponding biological component into a so-called biohybrid robot, thus physically using biology to augment technology. This has been done by Kuwana et al. (1996), who equipped a mobile robot with living silk-moth antennas, the electroantennogram signals they produced being sent to an external computer that translated them in actuator signals. In a pheromone plume, this robot exhibited a locomotion pattern similar to that of a male silk-moth and succeeded to locate a pheromone source. Likewise, Herr and Dennis (2004) built a swimming robot actuated by two explanted frog semitendinous muscles and controlled by an embedded microcontroller. The muscles got their energy from the glucose solution the fish was swimming in. Using open loop stimulation protocols, the robot performed basic maneuvers such as starting, stopping, turning and straight-line swimming at a maximum speed of 1/3 body-lengths/second.

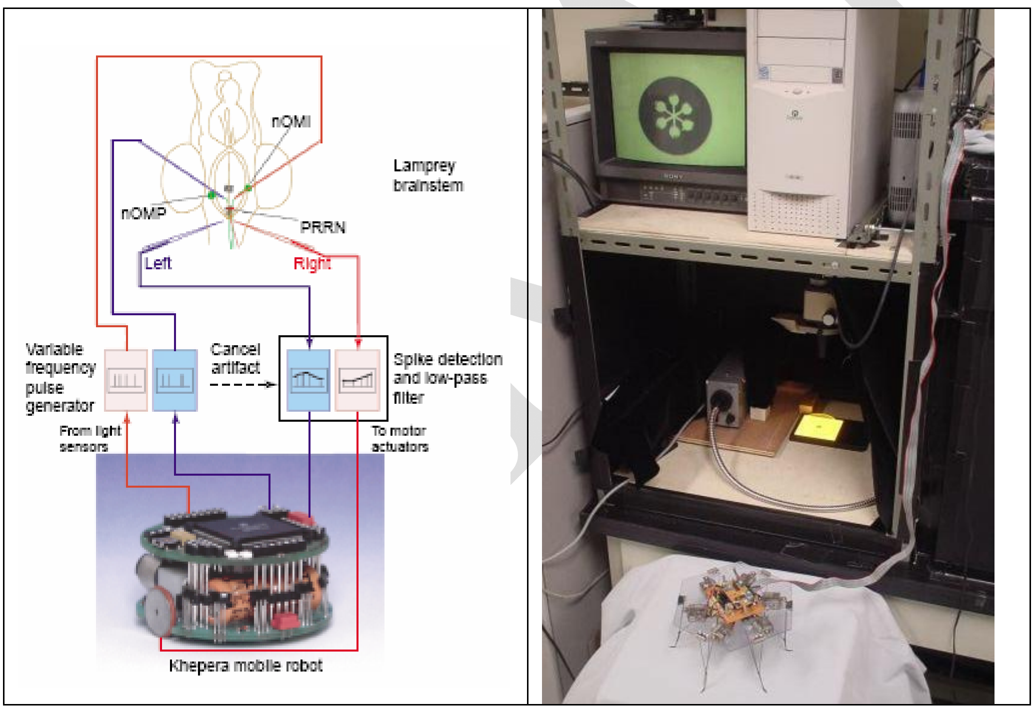


Fig. 27. Left: a robot controlled by a lamprey brainstem. Right: a robot controlled by a slime mold.

Bakkum et al. (2004) review a series of experiences in which cultures of real neurons are used to control robots. At Northwestern University, for instance, the part of the lamprey's brain that works to keep the fish's body balanced has been connected to a two-wheeled Khepera robot. In normal circumstances, the corresponding circuit receives vestibular and other sensory signals and issues motor commands to stabilize the orientation of the body during swimming. In the experimental setup that was used, light receptors on the robot sensed the surroundings, and a computer translated that information into electrical impulses that were fed into the lamprey's neurons. The latter interpreted the impulses as they would if they were trying to keep the fish swimming upright. The computer then translated the cells' signals back into electrical commands instructing the robot how to turn its wheels in response to a light (Fig. 27). Such experiments provided useful hints about the adaptive capacities of the neuronal circuit, demonstrating that different behaviors can be generated with different electrode locations and that the prolonged suppression of one input channel leads to altered responsiveness long after it has been restored (Reger et al., 2000).

A similar approach has been undertaken at the University of Southampton where, instead of calling upon numerous interconnected neurons, a single-celled organism -- *Physarum polycephalum*, a bright yellow slime mold that can grow to several metres in diameter and naturally shies away from light -- has been used to control the movement of an hexapod robot so that it kept out of light too and sought out dark places in which to hide itself. The experimenters grew the slime in a six-pointed star shape on top of a circuit and connected it remotely, via a computer, to the robot. Any light shone on sensors mounted on top of the robot was used to control light shone onto one of the six points of the circuit-mounted mold, each corresponding to a leg of the robot (Fig. 27). As the slime tried to get away from the light its movement was sensed by the circuit and used to control one of the robot's six legs. The robot then scrabbled away from bright lights as a mechanical embodiment of the mold (Tsuda et al., 2006).

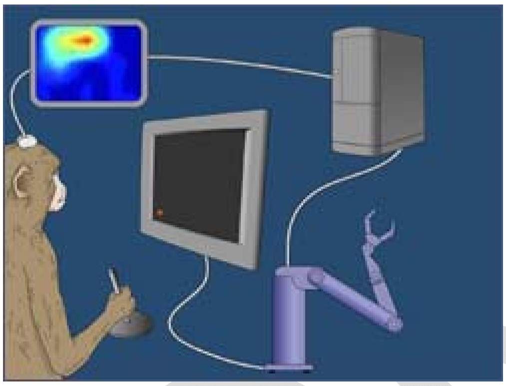


Fig. 28. A monkey brain controlling a robotic arm.

Finally, entire brains may be used to control robotic devices, as done at Duke University where rhesus monkeys were taught to consciously control the movement of a robot arm in real time, using only signals from their brains and visual feedback on a video screen. A neuronal model, which was developed by monitoring normal brain and muscle activity as the monkey moved its own arms, served to translate the brain signals from the monkey into movements of the robot arm. While the monkey was using a joystick to move a cursor on a computer screen, readings were taken from a few hundred neurons in the frontal and parietal regions of his brain. The activation of the biceps and wrist muscles was monitored, as were the velocity of the arms and the force of the grip. Once the neuronal model had developed an accurate level of prediction, the control of the cursor was switched from the joystick to the robotic arm, which in turn was controlled by the monkey's brain signals. At first the monkeys continued moving their own arms whilst carrying out the task, but in time they learned this was no longer necessary and stopped doing so (Lebedev et al., 2005) (Fig. 28).

Obviously, such technology affords great perspectives in the rehabilitation of people with brain and spinal cord damage, on the one side, while raising ethical issues, on the other side (anonymous, 2006). ETHICBOTS, an EC-sponsored project (http://ethicbots.na.infn.it/) is devoted to the identification and analysis of techno-ethical issues concerning the integration of human beings and artificial devices. Obviously, such concerns need to be extended to other animals as well, in cases where, for example, a living Madagascar Hissing Cockroach is placed atop a modified trackball to control a three-wheeled robot as part of an artistic project (http://www.conceptlab.com/roachbot/).

Finally, this Handbook's chapter 34 on exoskeletons provides other examples of the integration of human beings and artificial devices, while chapter 65 insists on the social and ethical implications of robotics.

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61.9 Discussion

It appears that almost all the continuum evocated in the Introduction has been covered by the numerous realizations described in this review. In particular, it should be clear that a kangaroo-shaped toy-robot has almost nothing of a real kangaroo, and that some of the devices that afford a robot a sense of touch or smell do reproduce a natural functionality, but certainly not the exact way it is implemented in a living creature. Such realizations are clearly bioinspired, but definitely not biomimetic, and they must be placed near the continuum's first extremity. Towards the other extremity, the optoelectronic circuits that copy the mechanisms implementing visual reflexes in the fly, or the artificial neural networks that copy the brain structures involved in navigation, action-selection and planning in mammals capitalize on almost all the relevant and currently available biological knowledge. They are clearly biomimetic even if their degree of realism may certainly be improved, if only because there are still a lot of discoveries to be made regarding the inner workings of these mechanisms and structures in vivo.

Noticing that important recent achievements in robotics have been more or less inspired by living systems does not entail that purely engineering approaches to the field have not also lead to spectacular advances -- as evidenced by numerous chapters in this Handbook. Conversely, under the pretext that Nature never invented the wheel[2], the jet plane or the laser range-finder, denying any usefulness to bioinspired approaches to robotics would sound like rearguard action. Instead, the interesting issue is that of delineating the applications for which such approaches are the most likely to be useful to robotics. In this perspective, the main lesson to be drawn from this review is probably that, if human inventions may be irreplaceable for optimizing a given functionality in rather predictable circumstances, drawing inspiration from the solutions discovered via natural tinkering (Jacob, 1977) may be particularly useful at finding operational compromises to multi-optimization problems raised by survival issues in unpredictable environments, i.e., to issues that engineers carefully postponed as much as possible up to now. Indeed, probably few people would deny that the capacities of autonomy and adaptation exhibited by living creatures far exceed those of current robots, which are seldom confronted with the necessity of coping with permanent changes in their external environment or in their inner needs, motivations or emotions, nor at the constraint of freeing themselves from human-delivered energy resources.

[2] In fact, microscopic wheels do exist in nature such as in ATP synthase and bacterial flagellum. Additionally, the wheel-like locomotion of tumbleweed balls across the desert has inspired the JPL Tumbleweed rover, i.e., a quasi-spherical vehicle intended to traverse a planetary surface with a rolling and/or bouncing motion driven by the wind (Behar et al., 2004).

Besides the fact that numerous sensors, actuators or control architectures in animals are often still more efficient than the artificial devices they have inspired -- either for reasons tied to technological limitations or to lack of biological knowledge -- perhaps the principal reason of the superiority of animals over robots lies in their greater degree of integration. In fact, in about 3.5 billion years since the apparition of life on Earth, natural sensors, effectors and control architectures were offered enough time to co-evolve and produce coherent wholes, a process that contrasts strongly with current practice of engineers who often independently design and produce the various components that they later assemble in a given artifact. Unfortunately, the laws governing natural evolution and integration are far from being deciphered and exploited in a more efficient manner than in current evolutionary robotics applications.

This last remark is related to the observation that biologists, too, in their tendency to favor reductionist over holistic approaches, often postpone the consideration of integrative mechanism and processes that future robotics will mostly need. Indeed, in its endeavor to unravel the mechanisms and processes that sustain natural life, traditional biology usually seeks to decompose a system into its constituent sub-systems and then to study these sub-systems in isolation from one another, according to a top-down, analytical and reductionist approach. On the contrary, people involved in artificial life or robotics research attempt to reproduce given characteristics of living systems with man-made artifacts like computers or robots. Ideally, their approach is bottom-up and starts with a collection of entities or modules exhibiting properties or behaviors that are simple and well understood, and organizes them into more complex systems in which internal interactions generate emergent life-like properties. Obviously, fruitful interactions are to be expected between these people and biologists who will devote their research efforts to the kind of integrative considerations advocated here. Many such interactions are already in place, as demonstrated in this paper and several others in this Handbook.

61.10 Conclusion

This article reviewed numerous recent applications of bioinspired solutions to robotics. It seems likely that such solutions will prove to be even more useful as future robots will get confronted to similar survival issues than those experienced by animals in unpredictable environments. This will require subsequent progress in the corresponding biological knowledge, a process to which tight collaboration between numerous disciplines, including robotics, may well critically contribute.

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