60. Biologically Inspired Robots

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After having stressed the difference between bio-inspired and biomimetic robots, this chapter successively describes bio-inspired 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 are described. Finally, the chapter also reports related works on energetic autonomy, collective robotics, and biohybrid robots.

60.1 General Background

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, Antoni Gaudi's design of the still-unfinished Sagrada Familia cathedral in Barcelona displays countless borrowings from mineral and vegetal exuberance.

Although a similar tendency underlied all attempts at building automata or protorobots up to the middle of the last century [60.1], 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 led 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 planetary 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 [60.2].

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 chapter, which first reviews recent research efforts in bio-inspired morphologies, sensors, and actuators. Then, control architectures that, beyond mere reflexes, implement cognitive abilities – like memory or planning – or adaptive processes – like learning, evolution and development – will be described. Finally, the chapter will also report related works on energetic autonomy, collective robotics, and biohybrid robots.

It should be noted that this chapter will describe both bio-inspired and biomimetic realizations. In fact, these two terms characterize, respectively, the extremities of a continuum in 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 result and the means. Thus, bio-inspired 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 bio-inspired, whereas the reverse is not necessarily true, qualifying expressions like bio-inspired or biologically inspired will be preferentially used in this chapter.

60.2 Bio-inspired Morphologies

Although not comparable to that of real creatures, the diversity of bio-inspired morphologies that may be found in the realm of robotics is nevertheless quite impressive. Currently, a huge number of robots populates the terrestrial, as well as aquatic and aerial, environments and look like animals as diverse as dogs, kangaroos, sharks, dragonflies, or jellyfishes, not to mention humans (Fig. 60.1).

In nature, the morphology of an animal fits its ecology and behavior. In robotics applications, bio-inspired 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, such as Kismet at MIT [60.3] or WE-4RII at Waseda University [60.4], which are able to perceive and respond to human emotions, and do themselves express apparent emotions influencing their actions and behavior (Fig. 60.2a,b).

Likewise, the Uando robot of Osaka University [60.5] 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. 60.2c). See Chap. 58 for more references on human-friendly 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. 60.3) thanks to a dedicated hormone-like adaptive communication protocol [60.6, 7].

Chapter 39 is devoted to distributed and cellular robots and provides other examples of such reconfigurable robots.

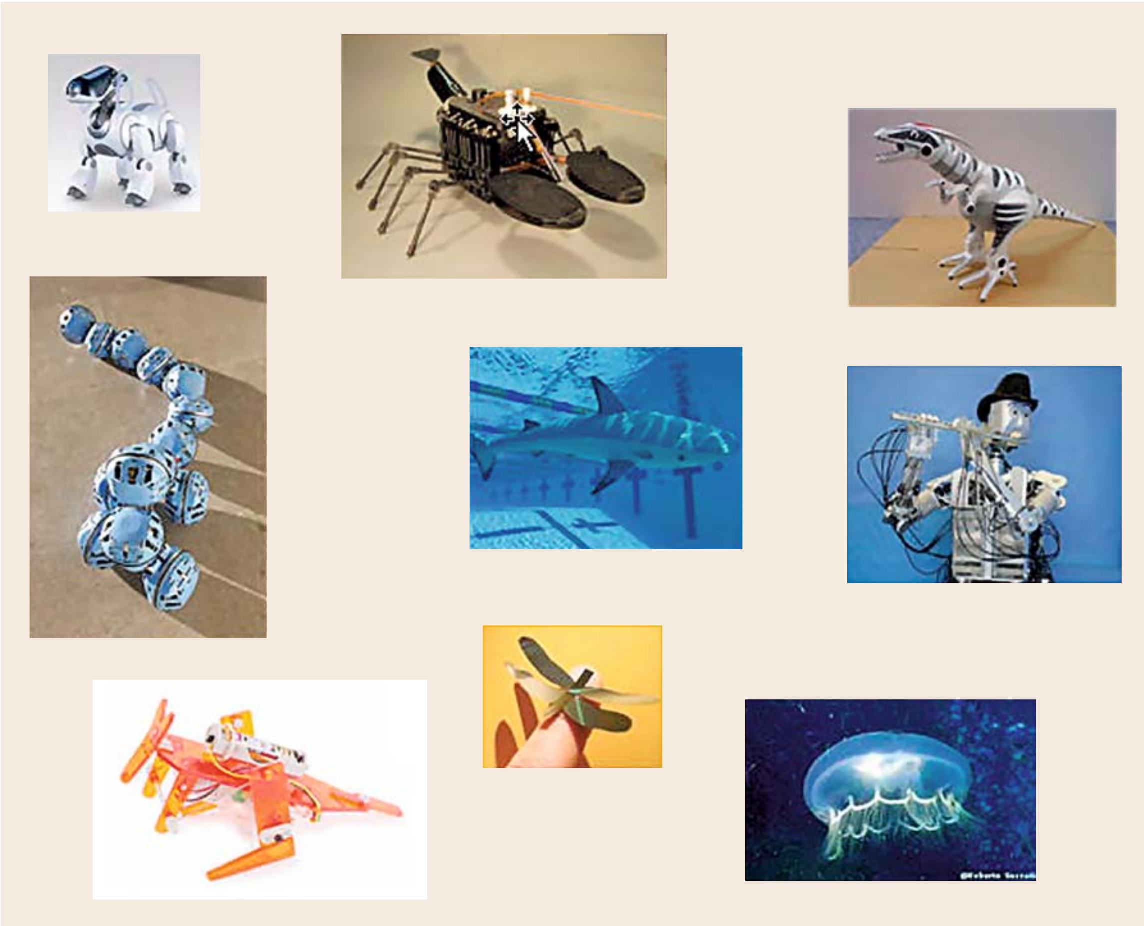

Fig. 60.1 A collection of zoomorphic robots

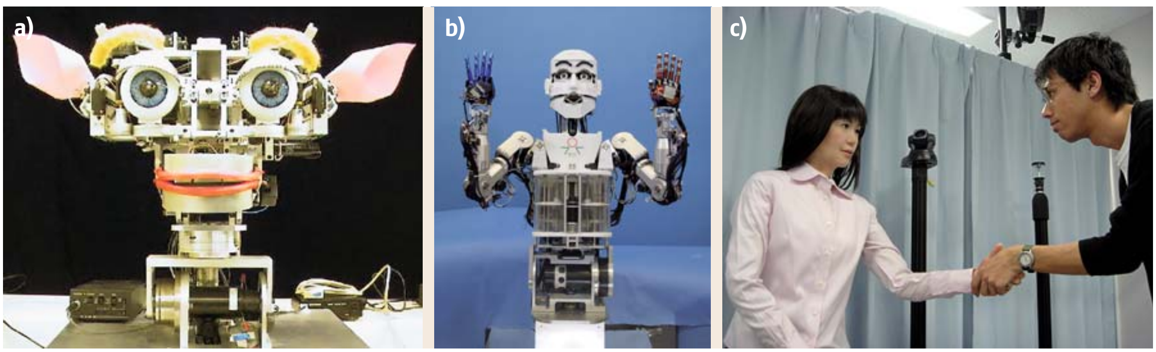

Fig. 60.2a–c Three humanoid robots. (a) Kismet ©Rodney Brooks, Computer Science and Artificial Intelligence Lab, MIT (b) WE-4RII ©Atsuo Takanishi Lab, Waseda University. (c) Uando ©Hiroshi Ishiguro, ATR Intelligent Robotics and Communication Lab, Osaka University

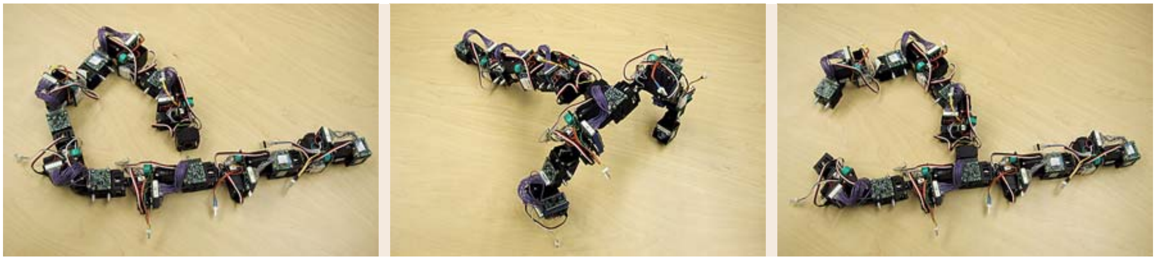

Fig. 60.3 A sequence reconfiguring a CONRO robot from a *snake* to a *T-shaped* creature with two legs. ©Wei-Min Shen, Polymorphic Robotics Laboratory, Univ. Southern California

60.3 Bio-inspired Sensors

60.3.1 Vision

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

Phototaxis is seldom the focus of dedicated research. It is rather usually implemented merely to force a robot to move and exhibit other capacities such as 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 in 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 flight, endow this insect with various reflexes mandatory for its survival. The biological knowledge thus acquired was exploited to implement optoelectronic devices allowing a terrestrial robot to wander in its environments while avoiding obstacles [60.8], or tethered aerial robots to track a contrasting target [60.9] or to automatically perform terrain-following, take-off, or landing [60.10] (Fig. 60.4).

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 with 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

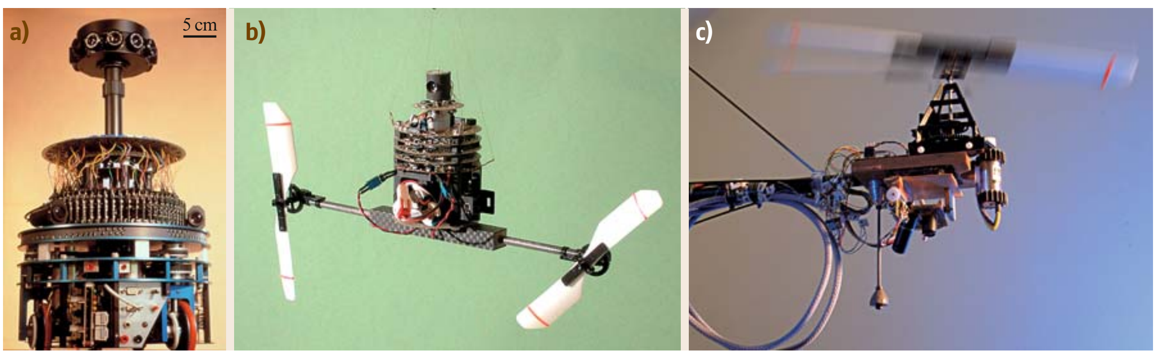

Fig. 60.4a–c Optoelectronic devices inspired by the housefly's compound eye. **(a)** Device for obstacle avoidance. **(b)** Device for target tracking. **(c)** Device for terrain following, take-off, and landing. ©CNRS Photothèque, Nicolas Franceschini, UMR6152 - Mouvement et Perception - Marseille

employed on mobile robot navigation in the Sahara desert [60.11].

Among the robotic realizations that are targeted at humanoid vision, some aim at integrating information provided by foveal and peripheral cameras. *Ude* et al. [60.12], 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. 60.5). Common alternatives to the use of two cameras per eye consist of using space-variant vision and, in particular, log-polar images. As an example, *Metta* [60.13] describes an attentional system that should be extended with modules for object recognition, trajectory tracking, and naive physics understanding during the natural interaction of a robot with the environment.

Other examples of robotic applications of perceptual processes underlying human vision are provided in Chap. 63 on perceptual robotics.

Vision-based simultaneous localization and mapping (SLAM) systems have also been implemented on humanoid robots, with the aim of increasing the autonomy of these machines. In particular, *Davison* et al. [60.14] used the HRP2 robot (Fig. 60.5) 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 three-dimensional 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 Chap. 37.

As another step towards autonomy in humanoid robots, mapping and planning capacities may be combined. *Michel* et al. [60.15], 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.

60.3.2 Audition

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

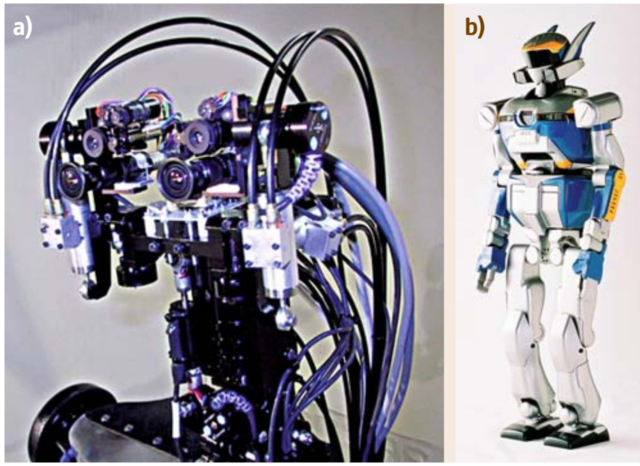

Fig. 60.5 (a) Four cameras implement foveal and peripheral vision in the head of the humanoid robot DB. Foveal cameras are above peripheral cameras. ©JST, ATR Robot developed by SARCOS. **(b)** The HRP2 humanoid robot ©Kawada Industries Inc./ National Institute of Advanced Industrial Science and Technology (AIST)

At the University of Edinburgh, numerous research efforts are devoted to 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. 60.6. In particular, an analogue very-large-scale integrated (VLSI) circuit models the auditory mechanism that enables a female cricket to meet a conspecific male or to evade a bat (by the calling song or the echolocation calls they produce, respectively). The results suggest that the mechanism outputs a directional signal to sounds ahead at calling song frequency and to sound behind at echolocation frequencies, and that this combination of responses simplifies later neural processing in the cricket [60.16]. This processing is the subject of complementary modeling efforts in which spiking neuron controllers are also tested on robots, thus allowing the exploration of the functionality of the 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 this may improve auditory tracking, particularly under conditions of random disturbance [60.17].

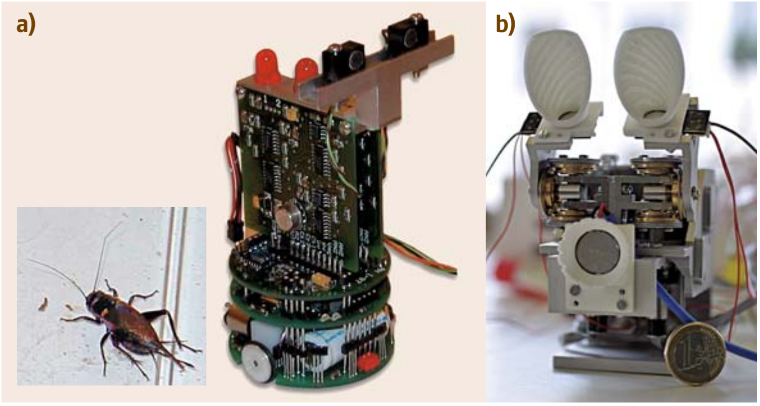

Fig. 60.6 **(a)** A Khepera robot equipped with a cricket-like auditory system. ©Barbara Webb, Institute for Perception, Action and Behaviour, University of Edinburgh. **(b)** The CIRCE robotic bat head ©Herbert Peremans, Active Perception Lab, Universiteit Antwerpen

Concerning more cognitive capacities, within the framework of the European Community (EC) project chiroptera-inspired robotic cephaloid (CIRCE), a bat head (Fig. 60.6) is used to investigate how the world is not just perceived, but actively explored, by bats. In particular, the work aims at identifying how various shapes, sizes, and movements influence the signals that the animal receives from its environment [60.18]. 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, which 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 [60.19]. Additional references to bio-inspired sonars are to be found in Chap. 21, dedicated to sonar sensing.

Nakadai et al. [60.20] describe a system that allows a humanoid robot to listen to a specific sound in under noisy environments (the human capability known as the *cocktail-party effect*) and to listen to several sources of speeches simultaneously, thus allowing it to cope with situations where someone or something playing sounds interrupts conversation (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 speech sources possible.

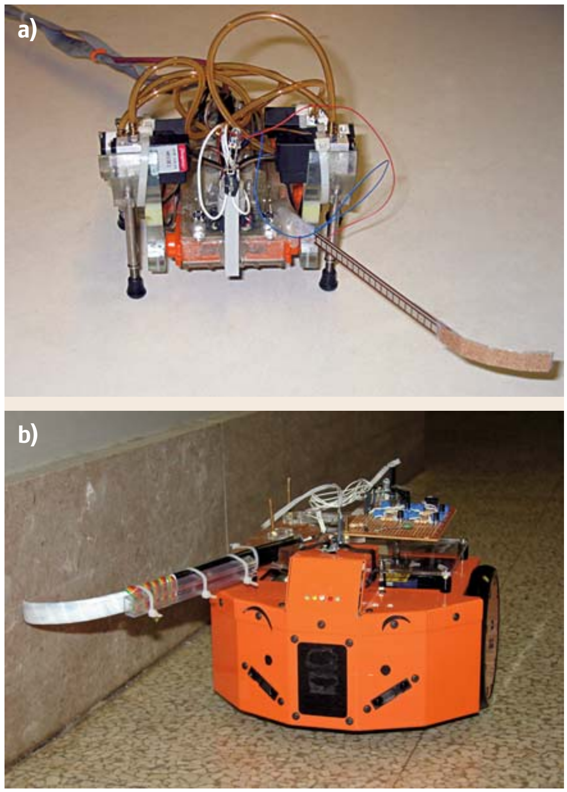

Fig. 60.7 **(a)** A simple antenna mounted on a Sprawlette robot ©Mark R. Cutkosky, Center for Design Research, Stanford University. **(b)** A more advanced tactile device ©Noah J. Cowan,Department of Mechanical Engineering, Johns Hopkins University

60.3.3 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 from 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 [60.21]. 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. 60.7).

While a cockroach's antenna consists of multiple rigid segments and is covered 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 in which 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* [60.22] 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.

Conversely, *Pearson* et al. [60.23] 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 ICEA (integrating cognition, emotion, and autonomy – http://www2.his.se/icea/) project whose primary aim is to develop a cognitive systems architecture based on the anatomy and physiology of the mammalian brain.

In the field of humanoid robotics, investigations on touch sensors are being conducted at the University of Tokyo, where a robotic hand calling upon organic transistors as pressure sensors (Fig. 60.8a) has been produced. The same technology served to make a flexible artificial skin that can sense both pressure and temperature (Fig. 60.8b), thus more closely imitating the human sense of touch [60.24].

Another step in this direction has been made at the University of Nebraska [60.25], 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

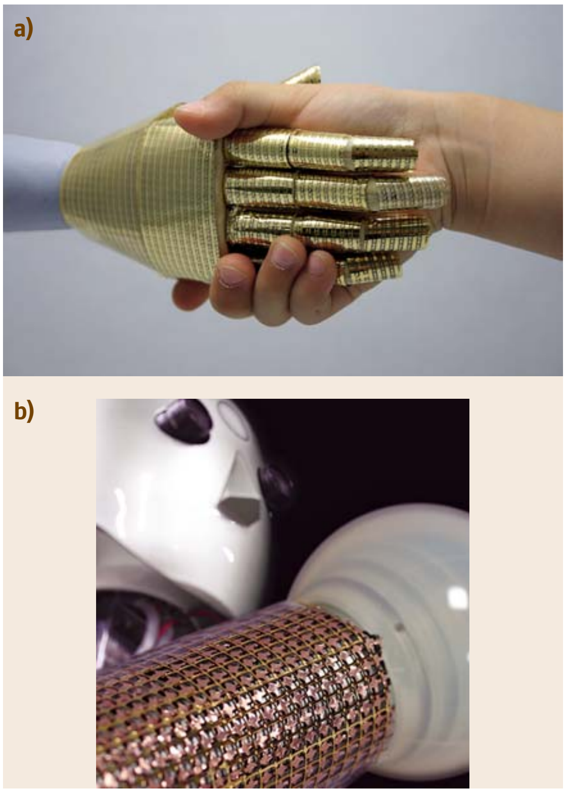

Fig. 60.8a,b Artificial skin devices at Tokyo University. **(a)** Pressure detection. **(b)** Pressure and temperature detection ©Takao Someya, Quantum-Phase Electronics Center, The University of Tokyo

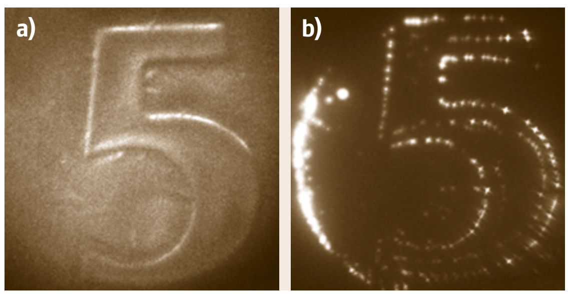

Fig. 60.9 **(a)** The optical image of a coin **(b)** The corresponding pressure image from the tactile sensor ©Ravi Saraf, Department of Chemical Engineering, University of Nebraska

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 placing a coin on this mechanical fingertip (Fig. 60.9).

Although such sensors deal 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.

60.3.4 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. This worm has a small nervous system (302 neurons), whose neurons and connectivity pattern have been completely characterized, so the neural circuit controlling chemotaxis is well known and, when implemented in a robot, proves to be able to cope with environmental variability and noise in sensory inputs [60.26]. 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, results obtained on the RoboLobster are put in perspective in [60.27].

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. 60.2) 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 [60.28].

60.3.5 Taste

A first robot with a sense of taste has recently been 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 health issues based on the information gathered. The latest developments afford the robot with the capacity to distinguish good wine from bad wine, and Camembert from Gouda (http://www.necst.co.jp/english/news/20061801/index.htm).

60.3.6 Internal Sensors

Whereas the previous *external* sensors all provide information about an animal's or a robot's external world, *internal* sensors provide information about a creature's internal state. Although such so-called idiothetic sensors are widespread in robotic applications, measuring variables such as 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 optokinetic reflexes), like those that are at work in the humanoid Cog robot mentioned later.

60.4 Bio-inspired Actuators

60.4.1 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 in search-and-rescue missions. The Salamandra Robotica (Fig. 60.10) developed at the Ecole Polytechnique Fédérale de Lausanne (EPFL) in Switzerland extends these approaches because it is the first robot that combines the three modes of locomotion – serpentine crawling, swimming, and walking – in a single robot. Being inspired by central pattern generators (CPG) found in vertebrate spinal cords, this work demonstrates how a primitive neural circuit for swimming, like the one found in the lamprey, can be extended by phylogenetically more recent limb oscillatory centers to explain the ability of salamanders to switch between swimming and walking. It also suggests a mechanism that explains how gait transition between swimming and walking can be obtained by simply varying the level of stimulation of the brainstem, and provides a potential explanation of how salamanders control their speed and direction of locomotion, by modulating the level and the asymmetry, respectively, of the drive applied to the spinal cord [60.29].

Other applications are sought within the framework of the EC biomimetic structures for locomotion in the human body (BIOLOCH) project. 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 [60.30]. 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. 60.10). 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*.

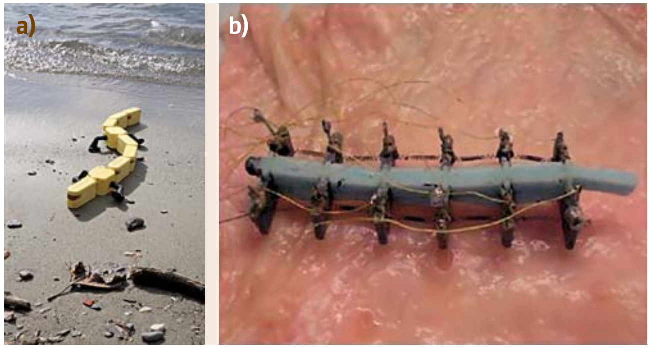

Fig. 60.10 **(a)** Salamandra Robotica, a robot that crawls, swims, and walks ©Photograph by A.Herzog, courtesy Biologically Inspired Robotics Group, EPFL **(b)** A worm-inspired robot designed to crawl through intestines ©Paolo Dario, Scuola Superiore Santa Anna, Pisa

Walking

Eight Legs. *Joseph Ayers* has developed a biomimetic robot based on the American lobster at the Marine Science Center of North Eastern University (Fig. 60.11). Capitalizing on recent advances in microcontrollers, smart materials, and microelectronic devices, this eight-legged ambulatory robot is intended for autonomous mine countermeasure operations in rivers, harbors, and/or the littoral zone of the ocean floor. Its control architecture supports a library of action patterns and reflexes – reverse-engineered from movies of lobsters behaving under the target conditions – that mediates tactile navigation, obstacle negotiation, and adaptation to surge.

The robot will have the overlying motivation to navigate on a specified compass heading. When encountering an obstacle, it will attempt to ascertain whether it is a mine candidate or not through dedicated sensors like an electronic nose, an acoustic hardness tester, or an active electric field perturbator. If the robot determines that the obstacle is not a mine candidate, it will decide whether to climb over the obstacle or to go around it using information supplied by its antennal sensors and claw-like surfaces. If climbing appears to be unfeasible, the robot will use a wall-following algorithm to go around the obstacle until it can resume its predetermined heading. This basic scenario will apply to almost all seafloor types because tactile queues from leg sensors will be used to determine whether the bottom is cobble, sand or hard, and because attitude reflexes will help with pitch and roll control [60.31].

Six Legs. In the performance energetics and dynamics of animal locomotion (PolyPEDAL) Laboratory at Berkeley, the observation that many animals self-stabilize to perturbations without a brain or its equivalent because control algorithms are embedded in their physical structure is widely exploited. Shape deposition manufacturing has allowed engineers to tune the legs of the SPRAWL family of hand-sized hexapedal robots inspired by the cockroach that are very fast (up to five body lengths per second), robust (hip-height obstacles), and that self-stabilize to perturbations without any active sensing [60.32]. One such robot is shown on Fig. 60.7. Capitalizing on previous work [60.33], 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 in Fig. 60.11. 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.

Water strider insects are able to walk on water because, instead of using buoyancy-like macroscale bodies, these very light and small creatures balance their weight using repulsive surface tension forces produced by the hydrophobic microhairs that cover their legs. In the NanoRobotics Laboratory of Carnegie Mellon University, Water Strider, a miniature microrobot, walks on water with legs made from hydrophobic Teflon®-coated wires and a body made of carbon fiber for minimal weight (Fig. 60.11). This tethered robot can successfully

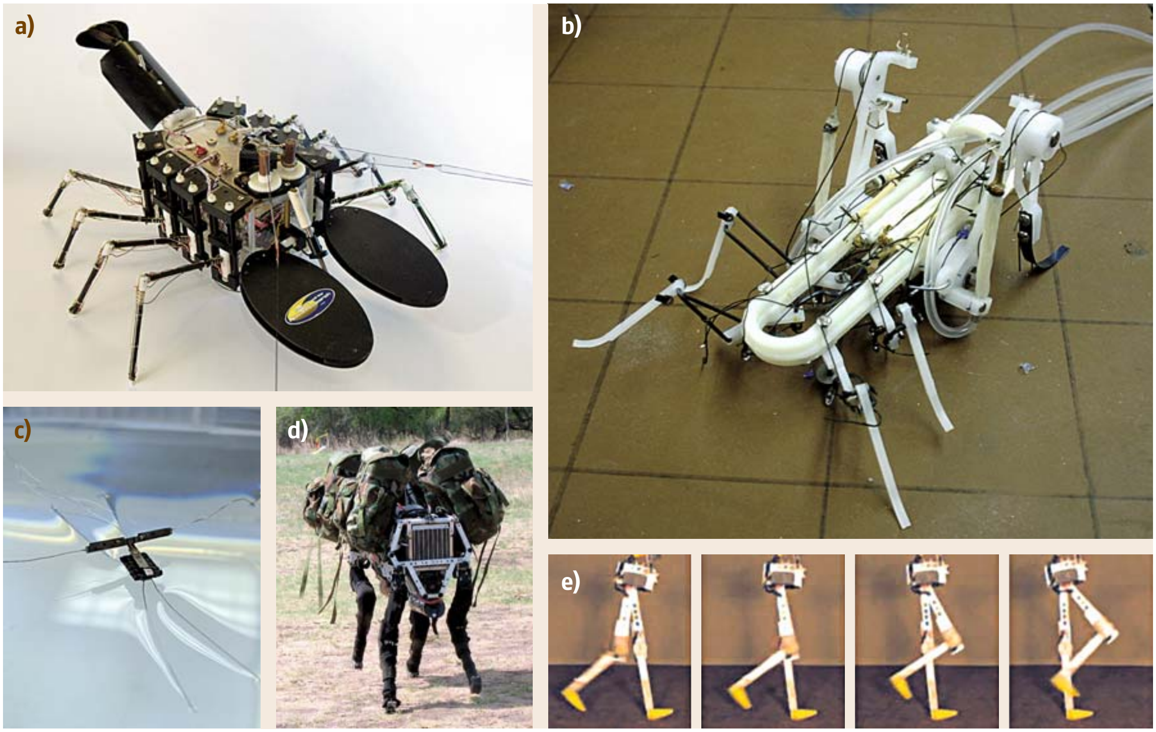

Fig. 60.11 **(a)** The lobster robot of Northeastern University ©Joseph Ayers, Department of Biology and Marine Science Center, Northeastern University. **(b)** The cricket robot from CaseWestern Reserve University ©Roger D. Quinn, Mechanical and Aerospace Engineering, Case Western Reserve University. **(c)** The Water Strider robot. ©Metin Sitti, NanoRobotics Lab, Carnegie Mellon University. **(d)** BigDog from Boston Dynamics ©Boston Dynamics, 2007. **(e)** RunBot from Stirling University ©Tao Geng, Department of Psychology University of Stirling.

move forward and backward, and can also make turns. Its maximum speed in forward motion is 2.3 cm/s. In the future, environmental monitoring applications on dams, lakes, sea, etc. would become possible using a network of these robots with miniature sensors and an onboard power source and electronics [60.34].

Four Legs. Engineers from Boston Dynamics claim to have developed *the most advanced quadruped robot on Earth* for the US Army. Called BigDog, it walks, runs, and climbs on rough terrain, and carries heavy loads. Being the size of a large dog or a small mule, measuring 1 m long and 0.7 m tall, and weighing 75 kg, 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. 60.11). Another quadruped with amazing locomotion capabilities is Scout II, presumably the world's first galloping robot, developed at McGill University [60.35]. 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.

Two Legs. 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. 60.11). This robot has some special mechanical features, e.g., small curved feet allowing rolling action and a properly positioned center of mass, which 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 can be 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 [60.36].

Additional references to legged robots can be found in Chap. 16.

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. 60.12). Geckos can climb up walls and across ceilings thanks to roughly half a million 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, which allow the gecko's feet to adhere. Conversely, if the hair is levered upward at a 30° 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 [60.37].

The robots in scansorial environments (RiSE) project funded by the Defense Advanced Research Projects Agency (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 [60.38, 39].

Jumping

In the perspective of environment exploration and monitoring, *Scarfogliero* et al. [60.40] describe a lightweight microrobot that demonstrates that jumping can be more

Fig. 60.12 Stickybot, the artificial gecko ©Mark R. Cutkosky, Stanford University Center for Design Research

energetically efficient than just walking or climbing, and can be used to overcome obstacles and uneven terrains. During the flight phase, energy from an electric micromotor is collected in the robot's springs, and is released by a click mechanism during take-off. In this way the instantaneous power delivered by the rear legs is much higher than that 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 build 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 designed two robotic fish, *RoboTuna*

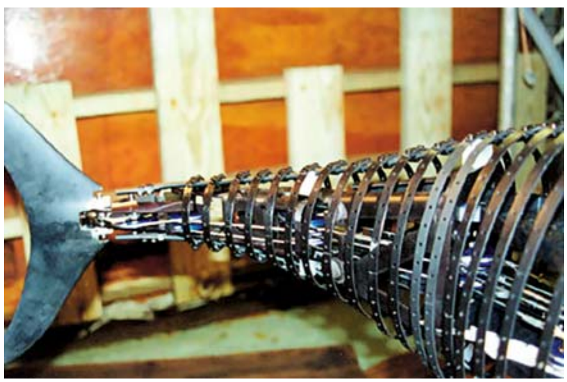

Fig. 60.13 The tail of RoboTuna at MIT ©Michael Triantafyllou, MIT Towing Tank

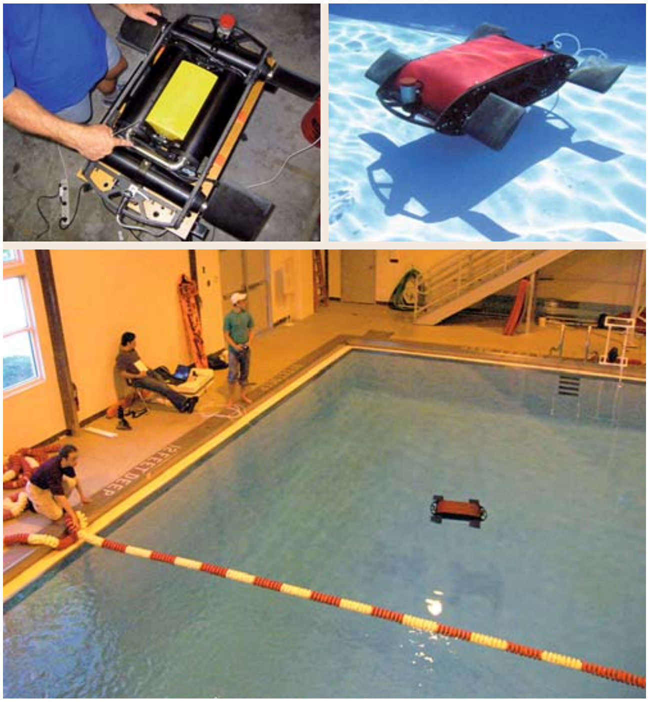

Fig. 60.14 The robot Madeleine ©John H. Long, Jr, Interdisciplinary Robotics Research Laboratory, Vassar College

and *RoboPike*, which use servo motors and spring element spines (Fig. 60.13), and serve to demonstrate the advantages of flapping foil propulsion. It has thus been shown that RoboTuna can reduce its drag by more than 70% compared to the same body towed straight and

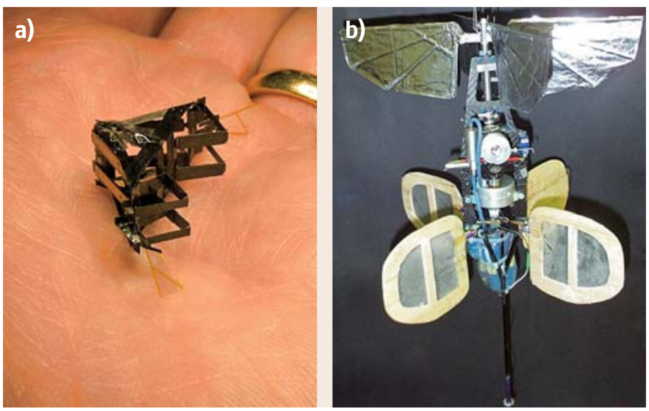

Fig. 60.15a,b Flapping-wing robots. **(a)** MFI ©Ronald Fearing, Berkeley's Electrical Engineering and Computer Science Department. **(b)** Mentor ©James DeLaurier, Institute for Aerospace Studies, University of Toronto

rigid [60.41]. 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 [60.42].

The robot Madeleine of Vassar College imitates the design of a turtle. Measuring 80×30 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 the latter are operated by electric motors connected to an onboard computer (Fig. 60.14). Because it can swim underwater using four flippers, like many extinct animals, or with two flippers, like modern animals, this robot has been used to investigate 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 create turbulence that interferes with the rear flippers' ability to generate forward propulsion – but does increase energy use. This may explain why natural selection favored two-flipper over four-flipper creatures like the plesiosaurs, and why four-flipper animals such as penguins, sea turtles, and seals use only two of their limbs for propulsion [60.43].

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 robots 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 necessary 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 in 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 stable flight in hovering mode [60.44, 45]. A first MFI platform, which flaps its two wings and is the right size, has already been produced (Fig. 60.15).

The four-winged ornithopter Mentor (Fig. 60.15), which is being developed at the University of Toronto as part of a general research effort targeted at flapping-wing flight [60.46, 47], is said to be the first artificial flapping-wing 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 enhance lift by clapping its wings together, then flinging them apart at high speeds. This augments the lift-producing bound vorticity on the wings. Likewise, the aircraft demonstrated the capability to shift from hovering to horizontal flight, which inspires current research. Mentor is about 30 cm long and weighs about 0.5 kg, but engineers eventually hope to shrink it to hummingbird size and weight. Other comparable micro aerial vehicle (MAV) devices are reported in [60.48, 49].

On a much larger scale, a few manned flapping-wing robots have also been designed. In Votkinsk in the 1990s, *Toporov* built a tow-launched biplane ornithopter that could reportedly be made to climb and fly for 200 m as a result of the pilot's muscular effort [60.50]. More recently, within the Ornithopter project of SRI International and the University of Toronto [60.51], the two-winged Flapper plane has flown for 14 s 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. A description of previous attempts at making such a platform fly is available in [60.52].

Fig. 60.16 The OCTARM robot ©Ian Walker, Department of Electrical and Computer Engineering, Clemson University

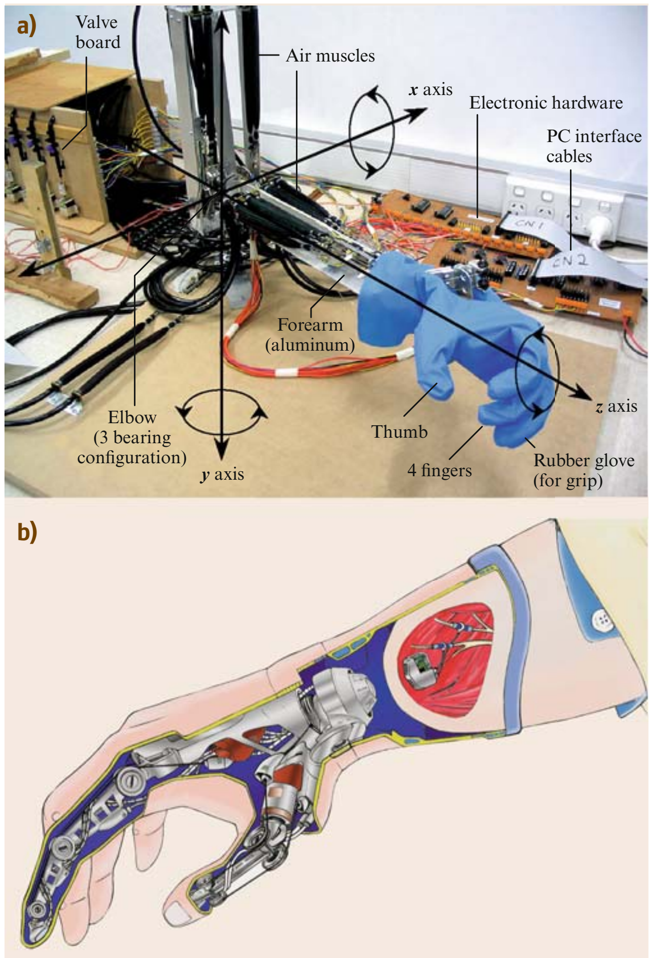

Fig. 60.17 (a) The humanoid hand of Curtin University of Technology. ©Euan Lindsay and Peter Scarfe, Mechatronic Engineering, Curtin University of Technology **(b)**The Cyberhand project ©Project Cyberhand (IST-2001-35094) and Scuola Superiore Santa Anna, Pisa

60.4.2 Grasping

When hunting and grabbing food, the octopus uses all the flexibility its arms are capable of. However, 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. [60.53] 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, this work in turn is leading to the development of artificial devices based on both electroactive polymers and pneumatic McKibben muscles, as well as to novel approaches to motion planning and operator interfaces for the so-called OCTARM robot (Fig. 60.16). Likewise, inspired by biological trunks and tentacles, a multisection 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 [60.54].

Human grasping has inspired the humanoid hand developed at Curtin University of Technology by *Scarfe* and *Lindsay* [60.55]. The corresponding system presents ten 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. 60.17). A similar research is funded by the EC CYBERHAND project that aims at developing a cybernetic prosthetic hand [60.56]. It is hoped that the device will recreate the *lifelike* 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. 60.17).

Chapter 15 provides additional references to robot hands.

60.4.3 Drilling

Due to the ultraviolet flux in the surface layers of most bodies in the solar system, future astrobiological research is increasingly seeking to conduct subsurface penetration and drilling to detect the chemical signature for extant or extinct life. To address this issue, *Gao* et al. [60.57] present a bio-inspired micropenetrator 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 ovipositors 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).

60.5 Bio-inspired Control Architectures

Attempts at tackling the *whole iguana* challenge [60.58], 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 of the aforementioned 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 such as learning, evolution, and development may be incorporated, will be mentioned.

60.5.1 Behavior-Based Robotics

Under the aegis of so-called *behavior-based* robotics – to which Chap. 38 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* [60.59] may endow artificial animals with adaptive capacities that do not necessitate high-level reasoning [60.60]. Moreover, there are some indications that such control architecture may be at work in real animals, such as the coastal snail *Littorina* [60.61].

Likewise, the *schemas* that are used by *Arkin* and his students at the Georgia Institute of Technology to control numerous other robots [60.62] have roots in psychology [60.63] and neuroscience [60.64].

60.5.2 Learning Robots

Different bio-inspired 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. 60.18). The robot is equipped with legs that generate initial momentum, and with a computer vision system to figure out where to place its hand-like 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 handhold, and a reward signal when it succeeds. Thus, after a number of failed trials, the robot eventually succeeds in safely moving from one extremity of the scale to the other [60.65].

Bio-inspired 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 [60.66–68] for reviews). Likewise, reinforcement learning mechanisms inspired by the presumed function of dopaminergic neurons [60.69] may be associated with models based on the anatomy and physiology of basal ganglia and related structures [60.70,71], 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 subgoals the unexpected events 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* [60.72] (Fig. 60.18) – as a contribution to the EC project ICEA mentioned before.

MirrorBot, another EC project [60.73], 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

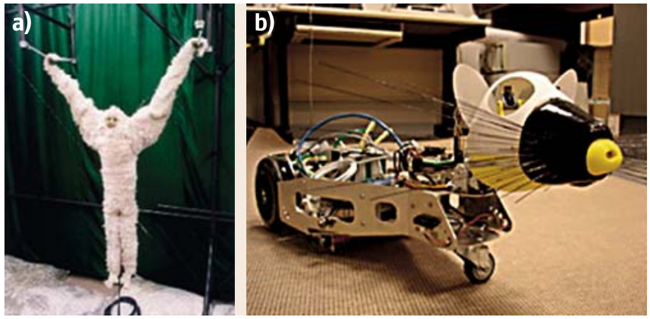

Fig. 60.18 **(a)** Brachiator, the artificial gibbon ©Toshio Fukuda, Department of Micro-Nano Systems Engineering, Nagoya University. **(b)** Psikharpax, the artificial rat ©Christophe Grand, Steve N'Guyen, Patrick Pirim, Bruno Gas, Ryad Benosman, ISIR, Université Paris 6

to cortical areas that are related to human language centers, and it seems that these neurons play a critical role in cortical networks establishing links between perception, action, and language [60.74]. 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 designated by their names [60.75].

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 become increasingly successful in coping with the environment. Among these devices, the robot Darwin VII is equipped with a charge-coupled device (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 neurons, 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 [60.76]. 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 [60.77]. 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 [60.78]. Besides its ability to learn to run mazes like rats, Darwin X has been thrown into a soccer match, and turned out to be victorious in the 2005 RoboCup US 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.

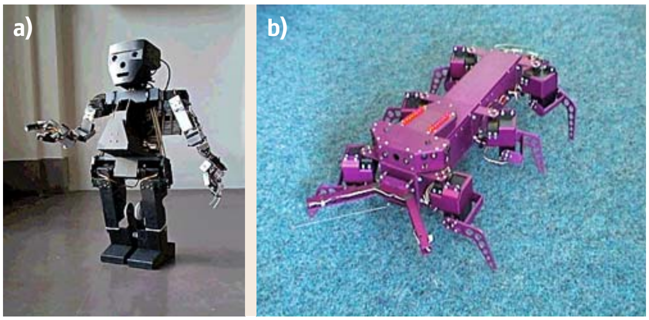

Fig. 60.19 **(a)** The robot Elvis. ©William Langdon, Mathematical Sciences, University of Essex **(b)** The robot SECT ©Jérôme Kodjabachian et David Filliat, AnimatLab et LIP6, Université Paris 6

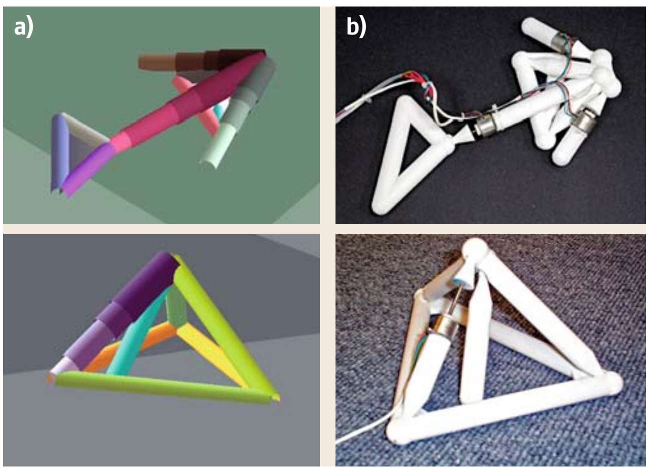

Fig. 60.20 **(a)** Simple robots whose morphology and control were evolved in simulation. **(b)** The corresponding physical realizations obtained through rapid-prototyping technology ©Jordan Pollack, Computer Science Department, Brandeis University

In the perspective of exploring the role that chaotic dynamics may play in self-organizing behavior, researchers involved in the NASA-funded self-organizing dynamically adaptable systems (SODAS) 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 navigate autonomously to a destination, the goal of the SODAS project is to enable robots to do the same on future National Aeronautics and Space Administration (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. [60.79] describe how, in a two-dimensional 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 bio-inspired approaches to the design of control architectures are to be found in Chap. 62, which is dedicated to neurorobotics.

60.5.3 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 [60.80].

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. 60.19a) with the motor orders sent to its effectors. Thus the robot is able to track and point a visual target [60.81]. In a similar manner, at the 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 the six-legged SECT robot (Fig. 60.19b) [60.82]. At the same university, simulated artificial evolution has been applied to the control of horizontal flight in an artificial bird, or to slope-soaring in a glider [60.83]. The corresponding controllers will be implemented on real platforms as a contribution to the Robur project [60.84].

For the genetically organized lifelike electromechanics (Golem) project at Brandeis University, *Lipson* and *Pollack* [60.85] went beyond the evolution of hardware controllers and demonstrated for the first time a path that allows the transfer of virtual diversity of morphology into reality. They thus conducted a set of experiments in which simple electromechanical systems composed of thermoplastic, linear actuators, and neurons evolved from scratch to yield physical locomoting machines (Fig. 60.20).

Additional references to evolutionary robotics can be found in Chap. 61.

60.5.4 Developing Robots

Two varieties of developmental processes are currently applied to robotics. The first 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 [60.86] 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 a methodology has been applied at the Paris VI University to evolve neural controllers for diverse rolling, walking, swimming, and flying animats or robots [60.87].

The second series of developmental process (see [60.88] for a review) are related to learning and aim at reproducing the successive sensory-motor and cognitive stages exhibited by developing animals, especially children [60.89]. As an example of such an endeavor, the upper-torso humanoid robot called Cog [60.90] (Fig. 60.21a), developed at MIT, has 22 DOFs and a variety of external and internal sensory systems, including visual, auditory, vestibular, kinesthetic, and tactile senses [60.91]. 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 the results already acquired are the development of mechanisms for reaching and grasping, for rhythmic movement control, for

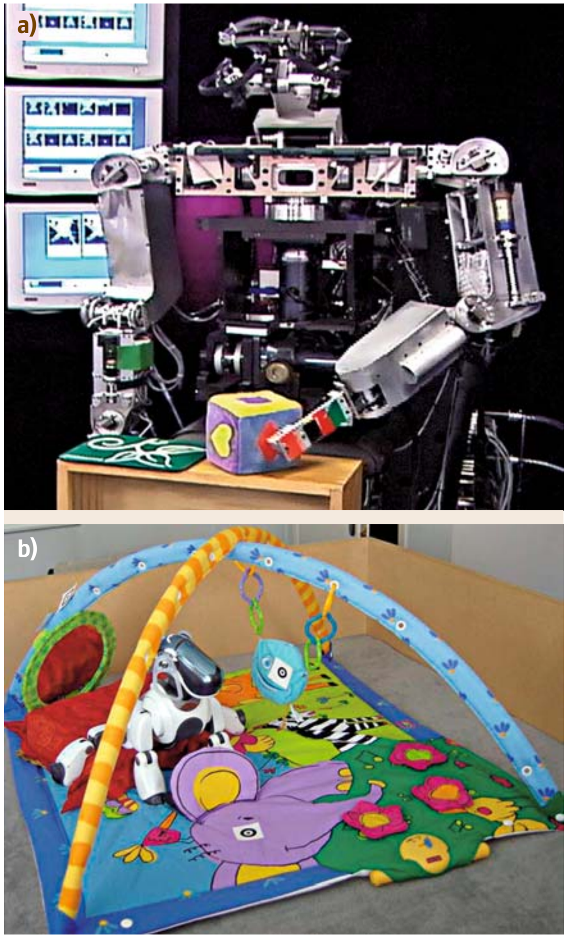

Fig. 60.21 (a) The Cog robot. ©Rodney Brooks, Computer Science and Artificial Intelligence Lab, MIT. **(b)** An Aibo robot in a playground environment ©Frédéric Kaplan, Sony Computer Science Laboratory, Paris

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 [60.92]. The latter expression is commonly used to design the set of cognitive skills that make it possible to attribute beliefs, goals, and desires to other individuals. In a similar perspective, at Sony Computer Science Laboratory (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. 60.21b) that tries 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 progressively shifts its attention to situations of increasing difficulty, avoiding situations in which nothing new can be learned [60.93].

60.6 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 to supply their energy needs. Very few attempts have been made in this direction yet. As a notable exception, Chew Chew was a 12-wheeled, train-like robot developed at the University of South Florida, which derived power through a microbial fuel cell (MFC) stomach (Fig. 60.22a). The stomach broke down refined sugar using *Escherichia coli* bacteria and then converted the chemical energy from that digestion process into electricity. The microbes from the bacteria fed on the sugar, which released electrons. These electrons, in turn, supplied a charge to the battery through a redox reaction. Moreover, the sugar cubes being completely dissolved by the microbes, the system produced very little waste [60.94].

Slugbot (Fig. 60.22b) was a robotic slug catcher developed at the Bristol Robotics Laboratory that was equipped with a long articulated arm at the end of which were located a camera used for detecting slugs and a gripper used for catching them. 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 [60.95]. Unfortunately, funding of the project ran out before researchers succeeded in refueling the robot's batteries through slug fermentation and methane production.

Although praiseworthy, these attempts did not provide convincing evidence that they could 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 Bristol Robotics Laboratory 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

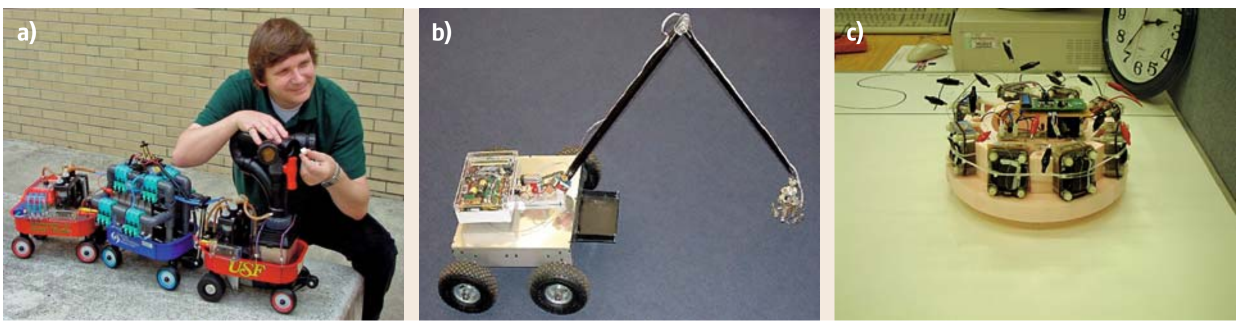

Fig. 60.22a–c Towards energetically autonomous robots: **(a)** Chew Chew ©Stuart Wilkinson, Mechanical Engineering Dept., University of South Florida, **(b)** Slugbot, and **(c)** EcoBot II ©Chris Melhuish, Bristol Robotics Laboratory, University of Bristol and University of the West of England

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. 60.22c). Right now, EcoBot II can crawl along at a top speed of about 2–4 cm every 15 min and obtains enough power to perform phototaxis while remotely reporting temperature measurements via radio at the same time [60.96]. This makes it the world's first robot to be performing four different types of behavior – sensing, processing, actuation, and communication – from unrefined biomass. These research efforts contribute to the EC project ICEA already mentioned.

60.7 Collective Robotics

Numerous research efforts contribute to the field of bio-inspired collective robotics [60.97] and several of them are described in Chap. 40, 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 [60.98] 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 swarmbot is an aggregate of s-bots – i. e., a collection of mobile robots able to self-assemble by connecting/disconnecting from each other. It can explore, navigate, and transport heavy objects on rough terrains in situations in which a single s-bot would have major problems achieving the task alone, like collectively passing over a gap too big for a single robot (Fig. 60.23) [60.99].

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 physicochemical parameters, and at tracking currents and upwellings [60.100]. 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 that the measurements they take are permanently as information-rich as possible.

Fig. 60.23 A swarm-bot passing a gap ©Francesco Mondada, Project Swarm-bot, EPFL

Fig. 60.24 Mars Entomopter and refueling rover. ©NASA Institute for Advanced Concepts

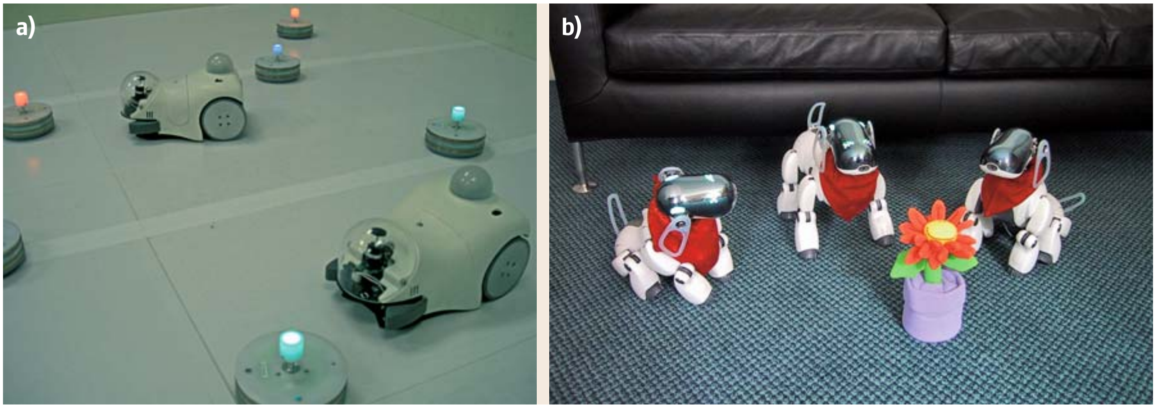

Fig. 60.25 **(a)** Cyber Rodents seeking battery packs ©Kenji Doya, Okinawa Institute of Science and Technology. **(b)** Three Sony Aibos paying attention to an object and possibly agreeing on a common word designating it ©Frédéric Kaplan, Sony Computer Science Laboratory, Paris

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 (Fig. 60.24), 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 while in flight, thereby making obstacle avoidance possible. Once airborne, the robots would flap at low altitude over Mars, sniffing 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 [60.101, 102] for terrestrial applications. In the same overall perspective, *Huntsberger* [60.103] describes the map-making memory and action-selection mechanism of the biologically inspired system for map-based autonomous rover control (BISMARC), an integrated control system for long-duration missions involving robots performing cooperative tasks, which is currently under development at the Jet Propulsion Laboratory (JPL) in Pasadena.

Besides cooperation, another variety of interaction is put to 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. 60.25a). 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 [60.104].

Finally, communication is at the heart of several projects that have been undertaken in the line of the so-called *talking heads* experiments [60.105] 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. 60.25b). Among such research efforts, the ECAgents project, which is sponsored by the EC, is developing 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* [60.106] studied how nonverbal 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.

60.8 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. [60.107], who equipped a mobile robot with living silk-moth antennas, the electroantennogram signals they produced being sent to an external computer that translated them into actuator signals. In a pheromone plume, this robot exhibited a locomotion pattern similar to that of a male silk moth and succeeded in locating a pheromone source. Likewise, *Herr* and *Dennis* [60.108] 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 that 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.

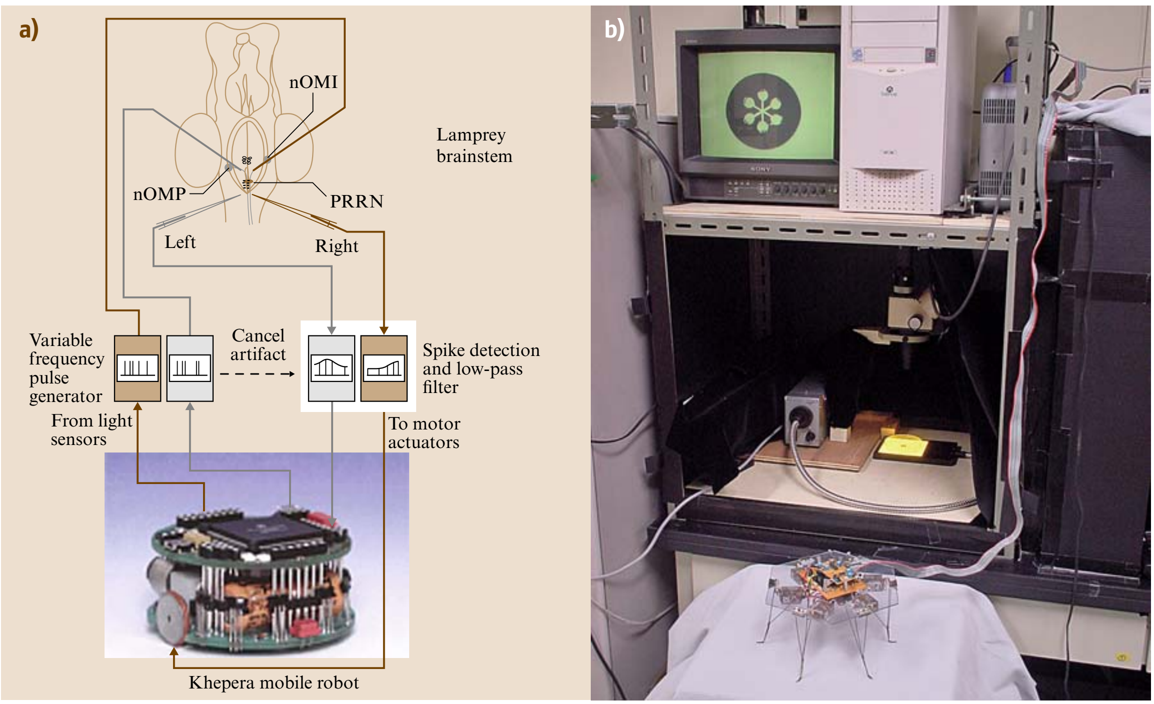

Fig. 60.26 **(a)** A robot controlled by a lamprey brainstem ©Sandro Mussa-Ivaldi, Depts. of Physiology, Physical Medicine & Rehabilitation and Biomedical Engineering, Northwestern University. **(b)** A robot controlled by a slime mold ©Soichiro Tsuda, Graduate School of Science and Technology, Kobe University

Bakkum et al. [60.109] 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 animal'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 animal 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. 60.26a). Such experiments have 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 [60.110].

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 meters in diameter and naturally shies away from light – has been used to control the movement of a hexapod robot so that it kept out of light and sought 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. 60.26b). 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 [60.111].

Finally, entire brains may be used to control robotic devices, as done at Duke University, where a rhesus monkey was taught to intentionally control the movement of a robot arm in real time, using only signals from his brain and visual feedback on a video screen. A neuronal model, which was developed by monitoring normal brain and muscle activity as a monkey moved his own arm, 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 monkey continued moving his own arm whilst carrying out the task, but in time he learned that this was no longer necessary and stopped doing so [60.112] (Fig. 60.27).

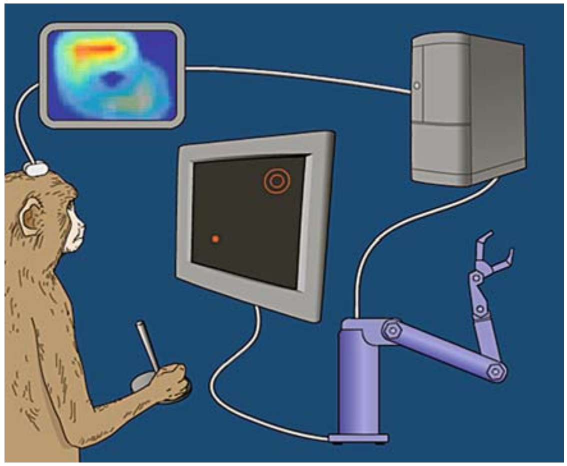

Fig. 60.27 A monkey brain controlling a robotic arm. After http://www.biotele.com/

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 [60.113]. ETHICBOTS, an EC-sponsored project [60.114] 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 [60.115].

Finally, Chap. 33 on exoskeletons provides other examples of the integration of human beings and artificial devices, while Chap. 64 insists on the social and ethical implications of robotics.

60.9 Discussion

It appears that almost all the continuum previously evoked 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 to do with 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 in the exact way in which it is implemented in a living creature. Such realizations are clearly bio-inspired, 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 inspired by living systems does not mean 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, the jet plane or the laser range-finder, denying any usefulness to bio-inspired approaches to robotics would sound like rearguard action. In fact, microscopic wheels do exist in nature such as in Adenosine 5'-triphosphate (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 [60.116]. Instead, the interesting issue is that of delineating the applications for which such approaches are most likely to be useful to robotics. In this regard, although we repeatedly deplored several years ago [60.117, 118] that the field of robotics did not favor a profusion of comparisons that would allow us to understand which architectures and working principles allow an animat or a robot to solve a given kind of problem in a particular environment, we are compelled to observe that the situation has not improved since that time. Considering, for instance, the profusion of models, working principles, physical realizations, and the like that characterize the robotic applications to navigation [60.66, 67], nothing would be more useful than systematic comparisons in which different robots would be confronted with the same problem, and different problems would be tackled by the same robot.

Be that as it may, 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 [60.119] may be particularly useful for finding operational compromises to multi-optimization problems raised by survival issues in unpredictable environments, i. e., to issues that engineers have 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.

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 for the superiority of animals over robots lies in their greater degree of integration. In fact, in the 3.5 billion years since the appearance of life on Earth, natural sensors, effectors, and control architectures have been offered enough time to coevolve and produce coherent wholes, a process that contrasts strongly with the current practice of engineers, who often independently design and produce the various components that they later assemble into 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 mechanisms and processes that future robotics will mostly need. Indeed, in its endeavor to unravel the mysteries of natural life, traditional biology usually seeks to decompose a system into its constituent subsystems and then to study these 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 such as 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 lifelike 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 chapter and several others in this handbook.

60.10 Conclusion

This chapter has reviewed numerous recent applications of bio-inspired solutions to robotics. It seems likely that such solutions will prove to be even more useful as future robots are confronted with similar survival issues to 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.

Further Reading

Interested readers may find useful additional information in the following textbooks:

- J. Ayers, J. Davis, A. Rudolph: *Neurotechnology for Biomimetic Robots* (MIT Press, Cambridge 2002)
- Y. Bar-Cohen: *Biomimetics – Biologically Inspired Technologies* (CRC, Boca Raton 2005)
- Y. Bar-Cohen, C. Breazeal: *Biologically Inspired Intelligent Robots* (SPIE, Bellingham 2003)
- R. Duro, J. Santos, M. Graña, J. Kacprzyk: *Biologically Inspired Robot Behavior Engineering* (Springer, Berlin, Heidelberg 2003)
- B. Webb, T.R. Consi: *Biorobotics. Methods and Applications* (MIT Press, Cambridge 2001)

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