Multimedia Contents

75. Biologically Inspired Robotics

Fumiya Iida, Auke Jan Ijspeert

Throughout the history of robotics research, nature has been providing numerous ideas and inspirations to robotics engineers. Small insect-like robots, for example, usually make use of reflexive behaviors to avoid obstacles during locomotion, whereas large bipedal robots are designed to control complex human-like leg for climbing up and down stairs. While providing an overview of bio-inspired robotics, this chapter particularly focus on research which aims to employ robotics systems and technologies for our deeper understanding of biological systems. Unlike most of the other robotics research where researchers attempt to develop robotic applications, these types of bio-inspired robots are generally developed to test unsolved hypotheses in biological sciences. Through close collaborations between biologists and roboticists, bio-inspired robotics research contributes not only to elucidating challenging questions in nature but also to developing novel technologies for robotics applications. In this chapter, we first provide a brief historical background of this research area and then an overview of ongoing research methodologies. A few representative case studies will detail the successful instances in which robotics technologies help identifying biological hypotheses. And finally we discuss challenges and perspectives in the field.

Biologically inspired robotics (or bio-inspired robotics in short) is a very broad research area because almost all robotic systems are, in one way or the other, inspired from biological systems. Therefore, there is no clear distinction between bio-inspired robots and the others, and there is no commonly agreed definition [75.1]. For example, legged robots that walk, hop, and run are usually regarded as bio-inspired robots because many biological systems rely on legged locomotion for their survival. On the other hand, many robotics researchers implement biological models of motion control and navigation onto wheeled platforms, which could also be regarded as bio-inspired robots [75.2].

75.1 General Background

The broad spectrum of bio-inspired robotics research is reflected to a variety of synonyms used in different scientific communities. For example, biomimetics and bionics are usually used to represent the types of research in which researchers observe biological systems and extract design principles for robotic applications. The terms bio-robotics and bio-engineering are also used interchangeably to biomimetics and bionics, but they often refer to engineered solutions specifically for biomedical applications. Another approach, usually classified as artificial life, biological cybernetics, or biophysics, investigates biological systems by using synthetic approaches. Here biological systems are typically viewed as mechanical and chemical entities and characterized by mechanistic models that are often very similar to the bio-inspired robots. The definitions and types of research studies conducted in these research areas are often overlapping, and many research projects provide results across the different areas.

While some of these research areas are also covered in the other chapters of this handbook, one of the most prominent, and more importantly useful, aspects of bio-inspired robotics lies in the contributions of robotics research for biological sciences. In contrast to the other robotics research, a significant number of bio-inspired robots were developed for the purpose of testing hypotheses concerning biological systems and for identifying the underlying mechanisms of biological systems that are very difficult to be clarified otherwise. In this chapter, we specifically focus on this aspect of bio-inspired robotics.

75.1.1 Brief History and Conceptual Background

There is a long history of the engineers' desire to replicating biological systems into artificial ones, including the famous examples of Japanese Karakuri dolls and Swiss automata several centuries ago (Fig. 75.1). Similarly, scientific efforts to use robotic systems to understand biological systems have also a relatively long history, which goes back even before the modern robotics started. One of the most influential examples in the earlier ages can be represented by the works in the field of cybernetics in which a number of system theories such as the concepts of feedback and feedforward were applied to understand phenomena in biological systems [75.3, 4].

The rise of neuroscience in the mid-twentieth century influenced bio-inspired robotics research significantly. In the 1950s, one of the first bio-inspired robots, Tortoises, was built by Grey Walter, a neurophysiologist. The work was mainly driven by biological questions, such as how a simple neuron connectivity can result in richness of sensory-motor behaviors, and a turtle-like robot consisting of analog electronics, sensors, and electric motors demonstrated reflexive behaviors as well as basic motor learning in autonomous robots [75.5]. Another physiologist, *Valentino Braitenberg*, also explored the power of *understanding by building* approach, which led to the famous thought experiments of Braitenberg Vehicles, i. e., a series of imaginary mobile robots that are still often used to teach the relationship between neural connectivity and sensory-motor behaviors [75.6].

The invention of digital computers was also another historical milestone in bio-inspired robotics. The pioneers of digital computers such as *John von Neumann* and *Alan Turing* provided significant influences in the biological studies through their seminal works on self-replication and self-organization [75.7, 8], and the subsequent foundation of the field of Artificial Intelligence in the 1950s was driven based on the understanding of human intelligence especially from the computational standpoint [75.9].

While the power of digital computers dominated bio-inspired robotics for a while, the study of insect-like reflexive behaviors became popular again in the 1980s with the emergence of behavior-based robotics. The intensive studies of this approach shed light on the massively parallel nature of motion control processes, and demonstrated behaviors that cannot be fully explained by the conventional *sense-think-act* style control approach [75.10, 11]. One of the main contributions of this line of studies lies in the fact that the diversity and flexibility of control architecture is essential in adaptive behaviors in real-world systems, and the complexity of behaviors is not necessarily originated in the complexity of controller but in physical system–environment interactions [75.12].

Since then the research on physical system–environment interactions has been very popular in the interdisciplinary community of embodied cognitive science and artificial intelligence in which roboticists, biologists, computer scientists, and physicists work together to look into further details of underlying mechanisms of adaptivity in biological systems. Here the body as a physical entity is not only considered as a necessary *container* of intelligent adaptive behaviors but it also plays a central role that induces self-organization of patterns and structures in adaptive intelligent behaviors [75.13–15]. In this context, robotics methodologies and technologies are used to investigate hypotheses about the roles of embodiment that cannot be easily tested in animals.

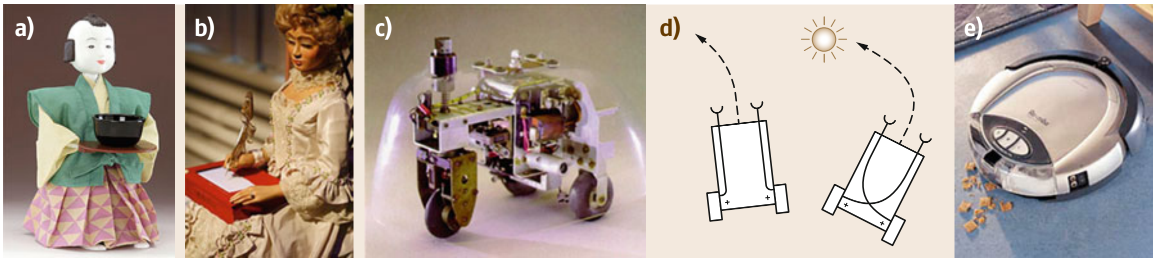

Fig.75.1a–e Examples of bio-inspired robots in the history. **(a)** Japanese Karakuri doll, **(b)** Swiss Automaton, **(c)** Grey Walter's Tortoises Robot (after [75.5]), **(d)** Braitenberg Vehicle (after [75.6]), and **(e)** a cleaning robot Roomba as an example of behavior-based robotics application

75.2 Methodology

In order to provide contributions to both robotics and biological sciences, bio-inspired robotics research usually follows a series of unique research processes which are not necessarily common to the other areas of robotics. This section first explains similarities and differences in robotics and biology research, and then introduces a set of important concepts, methodology, and research tools often used in the bio-inspired robotics.

75.2.1 Similarities and Differences in Robotics and Biology

Both robotics and biological research aim to obtain the basic understanding about autonomous and adaptive behaviors of complex systems, thus the scientific methodologies of these fields are usually very similar. For example, biologists usually start with finding an interesting problem in animals, that can be comparable to roboticists building robot prototypes of their interests as the first step of research. Second, the animals are carefully observed such that the underlying mechanisms can be efficiently and effectively analyzed, a step which roboticists also follow in the case of their robots. And finally, both biologists and roboticists develop hypothetical models to explain the mechanisms of their interests and test them through additional experiments and analyses. Here the modeling processes are also similar in both robotics and biology in a sense that they typically employ similar scientific methods, such as dynamics modeling tools, computational optimization techniques, and the other analysis methods of system engineering, for example.

There are, however, a number of fundamental differences in biological and robotics research, which are mostly originated in the fact that biological systems are *constructed* by considerably different design principles in nature. Although it is very difficult to cover all differences, the following aspects of biological systems characterize some of the major discrepancies from today's robotic systems.

Multipurpose Systems in Unstructured and Uncertain Environment

In contrast to most of the robotic systems that are designed to perform one type of task in a well-defined environment, all biological systems are intrinsically multipurpose systems that are designed for many tasks in undefined and uncertain environments. For example, animals need to process tasks such as regulating metabolism for self-sufficiency, protecting themselves from predators, mating, and reproducing. It is important for roboticists to know that (i) animals are not optimized for one of these tasks, but they are designed to conduct all of them, and (ii) they do so in a way that is not optimal in any sense, but just *good enough* to survive and reproduce. Therefore, it is often not a good idea to blindly copy a part of animals' designs and mechanisms into robotic systems because there could be an alternative optimal solution if the system has to do a single task in a well-defined environment. Robotics researchers are, however, able to learn many principles and mechanisms from biological systems, if they are interested in the systems that need to deal with many tasks in unstructured and uncertain environments.

Massively Parallel, Modular, and Redundant Structures

Biological systems are composed of highly redundant structures in their bodies [75.13]. For example, most of multicellular organisms have massively parallel muscle fibers constituting a muscle group, a skeletal joint controlled through multiple muscle groups, millions of nerve cells conducting parallel signal processing, and countless receptors sensing changes in the environment. If compared to our robotic systems today, biological systems have orders of magnitude larger numbers of such sensory, actuation, and computational units that have to be carefully considered in bio-inspired robotics research. In addition, the processes necessary for autonomy and adaptivity are generally highly decentralized in biological systems. The control of animals' arms and legs, for example, involves mechanical interactions of musculoskeletal structures, reflexive sensory-motor pathways in spinal cord, and more complex motion control and planning in the higher centers of nervous systems, which are running in parallel. The redundant structures of biological systems also provide an important discrepancy between animals and today's robots: most of the subsystems in a living organisms have great autonomy and adaptivity by themselves, as exemplified by the fact that individual cells in skins and bones as well as receptors and muscles have their own regulation mechanisms as metabolism and growth.

Self-Organization and Dynamic Changes of Entire Organisms

Another important discrepancy between animals and today's robots lies in the fact that there is no *human designers* behind animals, and all components in an organism have to be designed, assembled and repaired by itself. Consequently, every individual animal has to start its life smaller and gradually grow larger over time; every part of their bodies is continuously changing; sensory-motor control has to be continuously updated to reflect the changes in the bodies. It is particularly important for robotics researchers to consider that there are different timescales in these dynamic processes in biological systems (Fig. 75.2 [75.16]). Some of the different timescales can be represented by the continuous changes of body plans at the evolutionary processes, the changes of body sizes and muscle strength through ontogenetic timescale, and update of sensory-motor loops in here and now timescale.

75.2.2 Modeling Biological Systems

Modeling plays an essential role in biological sciences. Biological models are the representation of knowledge which is not only used to communicate scientific discoveries among researchers but also structuring research areas by labeling knowns and unknowns. To make research activities efficient and effective, there are many different ways to model biological systems such as descriptive/illustrative explanations, mathematical, physical, or chemical representations. From this perspective, the researchers in bio-inspired robotics have been exploring whether robotic platforms can be used as a scientific tool to develop models of biological systems, which leads to an alternative approach to elucidating biological hypotheses (Fig. 75.3). Robots are

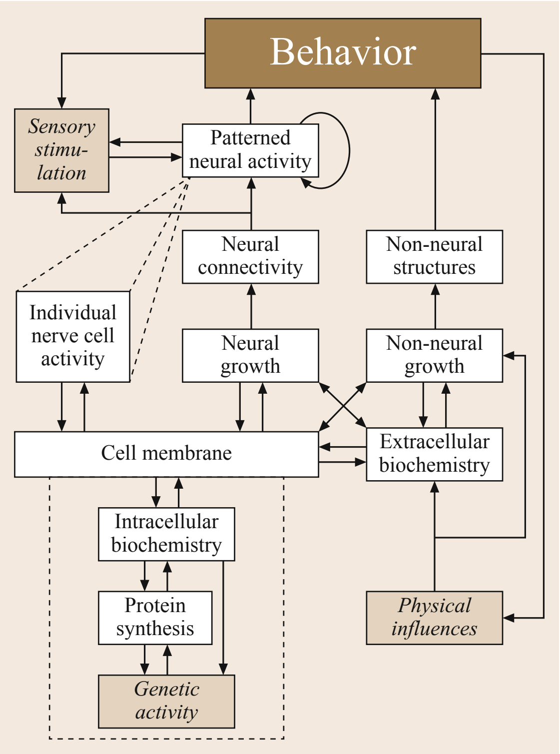

Fig. 75.2 Elements and their interactions that influence behaviors in biological systems. The model includes both neural and non-neural elements such as hormones (which constitute part of the extracellular biochemistry), bones, muscles, sensors, and their ontogenetic processes (after [75.16])

useful because they are physical entities as compared to simulated ones. First of all, by building models that can be implemented in a physical system, the process ensures whether the model in question is physically meaningful or not. In contrast, computationally simulated models always involve many approximations and simplifications which might affect the realism and therefore usefulness of the model (e.g., correctly modeling the hydrodynamics of a swimming fish is very hard in a simulation while it *comes for free* in a fish robot). Second, building robots directly contributes to the development of unconventional technological components.

Having said that, the use of robots as a scientific tool for biology is challenging because of the considerable discrepancies between animals and robots as explained in the previous subsection. A superficial copy of biological systems into a robotic counterpart is not a good idea because robots usually functions based on a completely different set of mechanisms, and the developed robot would most likely not explain much about the underlying mechanisms of biological

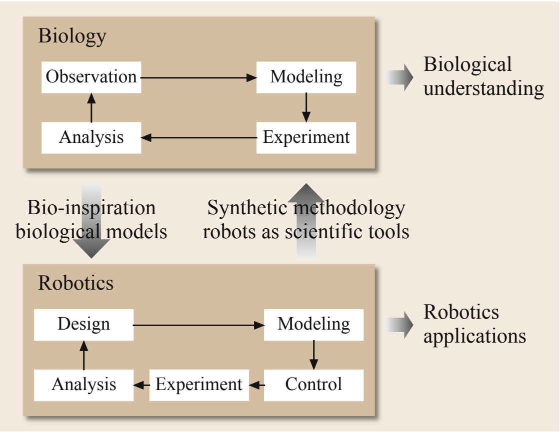

Fig. 75.3 Overview of bio-inspired robotics. Both biology and robotics follow similar research methods and interact to each other through models and tools, while they contribute to different objectives, i. e., understanding of biological systems or development of robotic applications

systems. Instead, it is particularly important to carefully examine what biological hypothesis we are interested in and we are testing by building robotic platforms. As an extreme example, if one is interested in understanding navigation mechanisms of animals, it is usually better to start with wheeled robot platforms than legged or flying ones, because the latter platforms would introduce unnecessary complexity in the research to examine a given hypothesis.

It is, however, not a trivial problem to find good biological hypotheses that can be applied in the bio-inspired robotics research. Biological systems are generally very complex, and hypotheses are not clearly separable from one question to another. Behaviors of animals are, for example, a result from neuronal activities of short and long terms, musculoskeletal dynamics, genetic and social interactions, and the mechanisms could also significantly vary in different individuals or species.

In order to deal with such a complexity in nature, *Full* and *Koditchek* have proposed an insightful methodology [75.17]. As shown in Fig. 75.4, they proposed a two-level modeling process which could benefit bio-inspired robotics research greatly: in the first level, a model should be simplified as much as possible such that it can be generalized over many species or in a large scale without being bothered too much by the details of complex animal structures. These models are called *templates*. A good example of this kind is the so-called spring-mass model that characterizes running behaviors of many different types of legged animals, even though it is an extremely simple model consisting of a point mass and a linear spring only. This approach enables researchers to examine the basic principles in nature, and despite its simplicity, the model can explain behavioral characteristics in a wide variety of animals even without considering detailed anatomical discrepancies between species. In the second level of modeling processes, templates should be enhanced by more details, which are called *anchors*. The investigations of the anchors are generally intended for more specific questions by adding redundancies of muscles or limbs or implementing more complex neuromuscular circuitry, for example. Through the template–anchor research approach, a research area can be effectively structured, and, for bio-inspired robotics research in particular, the simplified models can benefit robotics engineers to replicate behaviors of biological systems in a conceptual level.

Independently from the simplicity, it is also important to consider the purposes of models which

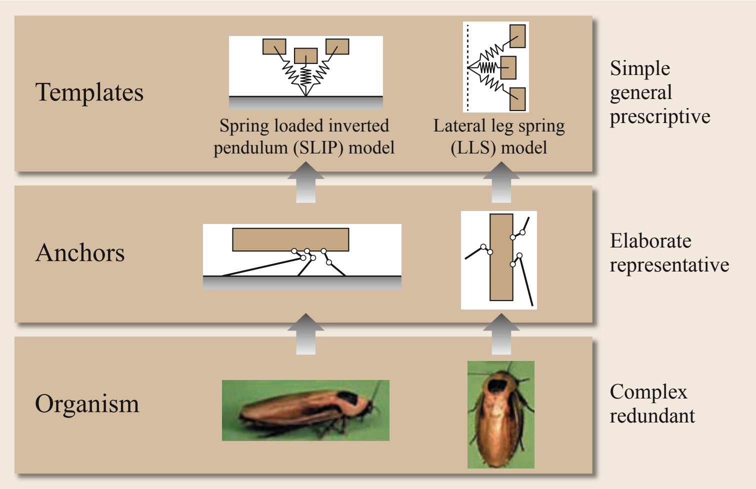

Fig. 75.4 Modeling hierarchy exemplified by the legged locomotion models. Animals can be abstracted into more elaborate and representative models (anchors) and/or simpler and more general models (templates) (after [75.17])

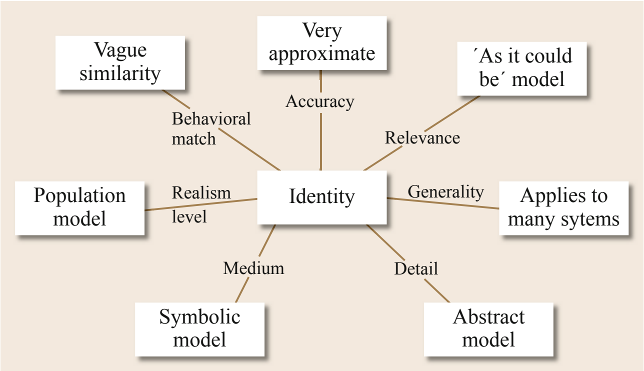

Fig. 75.5 Dimensions for describing models (after [75.18])

also influence how to structure bio-inspired robotics projects. After all, there is no correct model, but there are good or bad models with respect to the goal and hypothesis that are investigated. *Webb* has, for example, pointed out that there are seven major criteria with which we could evaluate models of bio-inspired robotics (Fig. 75.5 [75.18]):

1. Relevance to biology: as not all robotics research contributes to biological studies, it is important to clarify the degree to which a target robotic system and model are relevant.
2. Level: what are the base units of the model, and on what level of hierarchy in biological systems does the model attempt to represent?
3. Generality: a model could be developed for elucidating a mechanism of a specific system of interest, or for a more general mechanism that can be applied to many others. Therefore, the generality criterion considers how many systems the model intends to represent?
4. Abstraction: this criterion concerns the number and complexity of mechanisms included in the model.
5. Structural accuracy: there are many ways of representing systems but a question is the degree to which the model explains the internal mechanism of the target systems. In an extreme case, a model can behave the same at the level of input/output relationship, but it does not necessarily mean that the internal mechanism is the same.
6. Behavioral match: to what extent does the model behave like the target animal?
7. Medium of model: what is the model built from? A model can be made of mechanical, electrical, hydraulic, etc. or alternatively iconic, analog, symbolic, for example. Properly identifying these questions and the purpose of a robot is important. Indeed, there is a risk in bio-inspired robotics that a project is not useful to biology (i. e., it does not properly address a scientific question) nor to robotics (i. e., it does not perform better than a more conventional robot).

75.2.3 Research Methods and Tools

As it might have been already noticed, robotics technologies are used for many different purposes in the context of bio-inspired robotics. Robots are often used to *explore* new research areas and questions; many platforms were built and examined for the purpose of *testing biological hypotheses*; some of the other platforms were developed specifically for *application discovery* based on the identified principles in biological studies; and more recently, robotics technologies were *interfaced with or integrated into biological systems* to understand or enhance animals capabilities.

Even though there are many successful contributions of robotics technologies to biological studies, it is often not trivial to identify what are the good methods and tools for the given specific hypothesis or problems. In particular, one of the most critical questions is probably whether it is necessary to build a physical robotic platform or it is sufficient to investigate pseudo-robots in simulation. Building physical robots is usually very costly and requires significant amount of additional knowledge and know how; thus there are many case studies of bio-inspired robotics research conducted only in simulation in the past [75.19, 20]. This type of research generally makes use of physics models or physically realistic simulation environments that allow us to explore fairly complex artificial creatures. This approach is useful to explore a large parameter space which cannot be optimized in the real-world platforms. Also, the use of virtual creatures in the bio-inspired robotics research is also extremely important to investigate concepts and hypotheses that are not possible to test technologically such as robots with point masses, frictionless joints, self-replication, and robotic hardware evolution that cannot be possible with our today's technologies.

However, building physical robots is a *must* in some cases. For example, there are often target concepts or hypotheses involved in physical processes that are difficult to theoretically model, such as friction, impacts, thermodynamics, and hydro/aerodynamics. In addition, there has been an increasing interest in complex robotic systems that contain a considerable number of physical elements such as joints and actuators, simulation models of which tend to be vulnerable against accumulated errors. Another aspect of robots used as a scientific tool is to explore hypotheses that cannot be tested in nature. This approach is often called synthetic methodology (an understanding-by-building approach [75.13]), meaning that, by building and using artificial systems, we test biological principles that cannot be tested in conventional biological methods. The most representative example is the Braitenberg Vehicles, which we introduced in Sect. 75.1.1. Every vehicle has a set of oversimplified neural connections of an *animal* which does not exist in nature, but these creatures can explain important principles in biological systems. A similar approach was also extended to the studies of *life as it could be* [75.21, 22], in which, by creating biological phenomena in simulation or robots, a broader and more universal understanding of living systems. This methodology is particularly effective in the studies related to evolutionary biology, in which verifications of hypotheses are usually very challenging ([75.20, 23]; see also the chapter of evolutionary robotics).

75.3 Case Studies

This section introduces three research areas that have been particularly active in bio-inspired robotics in the last few decades. Here we highlight the case studies in which robotics researches contributed to our further understanding of biological systems, and we illustrate how the concepts and methods we introduced in the previous sections were applied to these studies.

75.3.1 Bio-Inspired Legged Locomotion

Legged locomotion has been one of the most popular research topics in bio-inspired robotics for a long time because it characterizes the salient differences between biological and artificial systems. Although legged locomotion is seemingly easy, useful, and efficient for biological systems to move around in complex environments, it is surprisingly difficult to understand the underlying mechanisms hence challenging to implement into robotic systems. The legged locomotion research has a relatively long history that goes back to the foundation of biomechanics in the seventeenth century [75.24], and it became particularly popular when the modern robotics was established in the 1970s [75.25, 26]. One of the main reasons that many robotics researchers were attracted by the issue of legged locomotion lies in the fact that it covers many of the discrepancies between biological and artificial systems that we discussed in Sect. 75.2.1. More specifically, legged systems have to carry out many different tasks in unstructured environments such as establishing sturdy footholds, avoiding obstacles, dealing with variations of payload and velocities, and changing gait patterns, for example; Legged systems have to deal with massive parallel processes which are required for coordinating many joints and muscles, as well as local reflexes and high-level decision and planning; And adaptivity is essential for legged systems because they need to maintain mobility in different environments as well as under significant changes of its body plan over growth processes, for example. While there are countless case studies in the past, this subsection focuses on the four key challenges of bio-inspired legged locomotion, i. e., stability, gait, energetics, and actuation, because they have been recognized as the long-standing challenges in bio-inspired legged locomotion. More comprehensive robotics research can be found in the section of legged locomotion.

Stability and Gait in Legged Locomotion

One of the main challenges in the study of legged locomotion is to uncover the mechanisms of motion stabilization against disturbances [75.27]. Biological systems usually make use of a variety of mechanisms including mechanical self-stabilization [75.28, 29], spinal reflexes [75.30, 31], central pattern generators [75.32], or sensory-motor control originated in the higher center of nervous system [75.33]. Because of the complexity of stabilization mechanisms in animals, bio-inspired robotics played an important role to systematically investigate the issues of stabilization through modeling of locomotion dynamics and reproducing the behaviors in legged robots of various kinds in the past.

Among others, bipedal walking was one of the most intensively studied topic areas which nicely illustrates how a synthetic approach could structure a research area of a complex biological problem. The backbone of this research area is the so-called *inverted pendulum walking model* which was originally investigated in biomechanics, and later used in the bio-inspired robotics research. The model considers the simplest physics representation of walking dynamics, i. e., a point mass is attached on a massless link, and simulates walking dynamics as the mass vaulting over the link [75.24]. This model can be, for example, physically implemented by the so-called rimless wheel that is the simplest *robotic* representation of the model (Fig. 75.6a; [75.34, 43]), and then, a slightly more complex configuration, the *compass gait model*, was proposed (Fig. 75.6b, [75.44]; VIDEO 111 shows an experiment of a compass gait bipedal robot locomotion on rough terrains). In contrast to the rimless wheel model that considers only stance leg dynamics during walking, the compass gait model has three masses with a passive hip joint, which allow us to investigate swing leg dynamics in addition to the stance

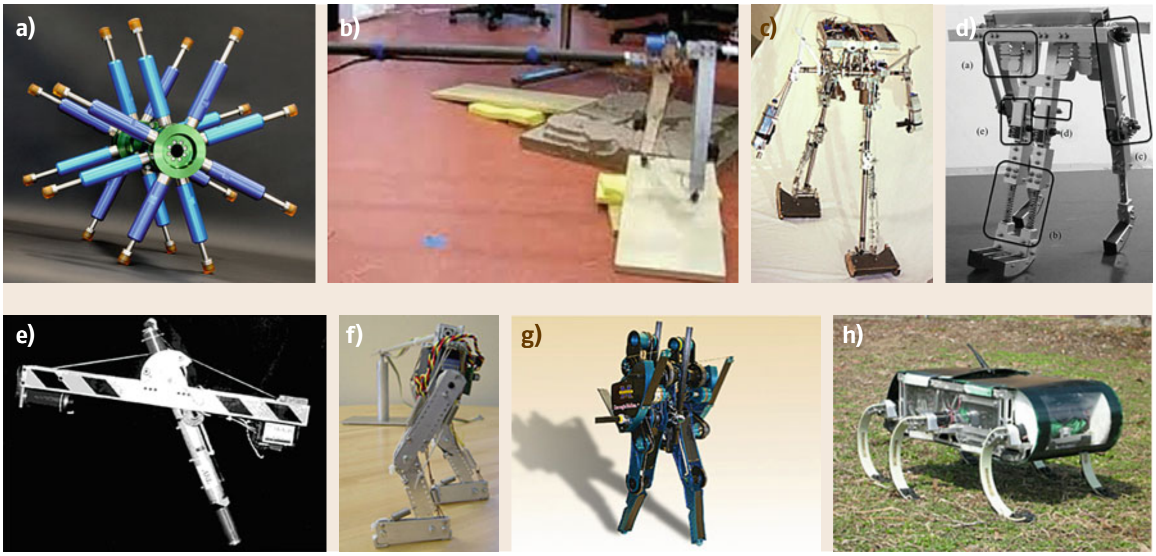

Fig.75.6a–h Examples of bio-inspired legged robots. **(a)** A physical implementation of rimless wheel walking model (after [75.34]), **(b)** A physical implementation of compass gait walking model (after [75.35, 36]), **(c)** passivity based bipedal walking robot (after [75.37]), **(d)** passive dynamic runner (after [75.38]), **(e)** energy efficient hopping robot (after [75.39]), **(f)** bipedal walking and running robot based on biarticlar springs (after [75.40]), **(g)** biped robot based on variable stiffness actuators (after [75.41]), and **(h)** hexapod robot based on spring mass dynamics (after [75.42])

leg [75.45]. An important implication of this line of research lies in the fact that, because of the simple formulations of complex dynamics, researchers were able to systematically investigate different aspects of the complex behaviors while keeping an overarching structure of research issues. These simple models were, for example, gradually and systematically enhance by integrating knee and ankle joints (Fig. 75.6c; [75.37, 43]), foot segments with variations of shapes, influences of mass distributions [75.46], influence of lateral motions, as well as a variety of advanced motion control architectures to demonstrate actuated locomotion in more complex environments [75.35, 36, 47, 48].

Although walking dynamics is a highly interesting challenge, the basic locomotion stability in walking is not sufficient to understand legged locomotion in nature, but stability has to be also maintained in different gait patterns, such as running because most of biological systems exhibit a rich variety of gaits. For this reason, running dynamics has also been studied intensively by investigating a simple model, i. e., the so-called spring-loaded inverted pendulum (SLIP model; [75.28, 49, 50]). The model consists of a point mass and a massless linear spring, on top of which many variations were proposed such as running models with nonlinear spring, segmented legs [75.51], swing leg dynamics, upper torso, lateral balancing [75.52], and wheel-like configuration (Fig. 75.6h [75.42]), for example. The SLIP model was also used to study walking dynamics and gait transitions between walking and running (Fig. 75.6f [75.40, 53]; VIDEO 110 shows an example of a biped robot walking and running). It is important to note that many of these models and robots were developed for the hypotheses difficult to test in biological systems. The biological legs are hardly linear springs but they consist of numerous active and nonlinear components. However, by examining these models and robots, we are able to learn the basic underlying principles such as the degree to which a spring-like behavior of legs could contribute to the stability of walking and running locomotion, for example. In addition, such an abstraction of biological body structures is very practical for robotics research as we are able to design and construct robots based on the underlying principles without replicating complex anatomical structures consisting of organic components.

Energy Efficiency and Bio-Inspired Actuation

Another considerable challenge in the study of bio-inspired legged locomotion is the principles for energy efficiency. It has been known that the locomotion efficiency of biological systems is known to be at least an order of magnitude better than most of the legged robots today but it is not fully understood why biological locomotion is so efficient. The complexity of the energetic problem in legged locomotion is originated in the many possible sources of energy dissipation such as frictional and damping losses in joints and muscles, mechanical impact losses at foot touchdown to the ground, metabolic costs, and energy required for acceleration and deceleration of body parts. Because of such a complexity, the bio-inspired robotics research has been significantly contributing to this problem by building and analyzing, for example, purely mechanical locomotion systems [75.38, 43], underactuated locomotion control [75.35, 37], the use of passive spring and self-excited vibration [75.39, 54], and exoskeleton devices [75.55]. All of these case studies were contributing to a comprehensive understanding of energy efficiency in biological locomotion [75.56], and some of the hypotheses have been analyzed and tested in biological systems.

In addition to the whole body dynamics, energy efficient locomotion has also been investigated at the level of actuation because the muscle-tendon systems play a major role in animals' efficient locomotion. Inspired from the biological models of muscles, this research trend started from the so-called series elastic actuators, which is an actuator unit containing a mechanical spring being installed in series to an electric motor [75.62]. The implementation of mechanical spring in an electric motor explained the unique characteristics such as storage of kinetic energy to elastic energy, shock absorption to protect mechanical transmission, and force-based feedback control, all of which are favorable for both biological and artificial legged systems. More recently, many researchers have been attempting to enhance the actuation mechanisms with variable stiffness and damping capabilities [75.41, 63] that are also expected to provide valuable insights into the roles of muscle properties in efficient legged locomotion.

75.3.2 Reflexes and Central Pattern Generators

Agility and adaptability of animals' locomotion are not only originated in mechanical dynamics as explained in the previous subsection, but there are also highly complex control systems regulating animals' motions. Usually animals control systems are labeled into four

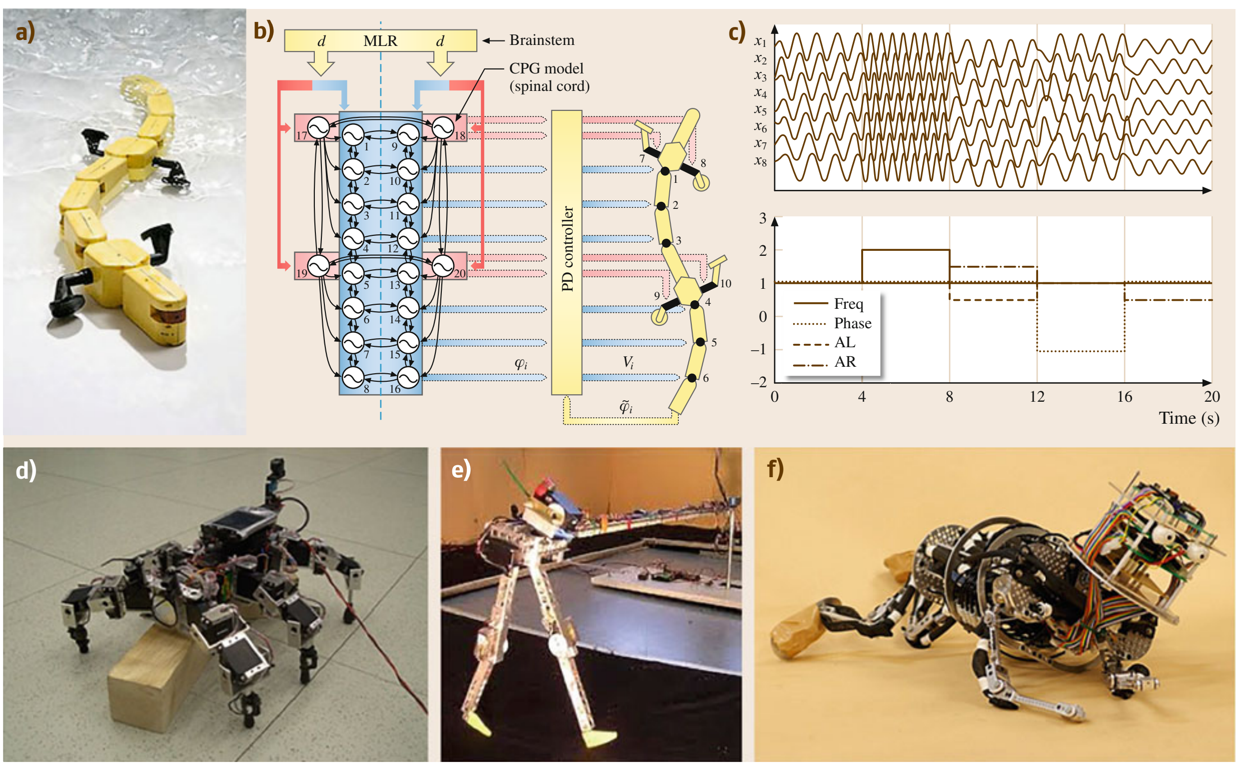

Fig.75.7a–f Robotic implementation of CPG models. **(a)** A salamander robot consisting of motorized modules, and **(b)** its control architecture. Every module has a servomotor which is controlled through a simulated CPG model. **(c)** Typical behavioral response of the CPG model (*upper figure*) with respect to a control signal (*lower figure*). One control input is sufficient to control smooth oscillations of multiple body segments because of coupled dynamics originated in the CPG model (after [75.57]). **(d,e)** A hexapod and biped robots that use CPG models to adapt to changes in the environment (after [75.58–60]). **(f)** A musculoskeletal humanoid robot that simulate developmental processes of human babies (after [75.61])

components: the musculoskeletal system, reflexes, central pattern generators (CPGs), and modulation by higher control centers. Bio-inspired robotics has been investigating these components individually or in combination, and resulted in a number of demonstrations of surprisingly robust robot locomotion (Fig. 75.7).

This research area has been historically investigated by the two distinguished approaches, i. e., the CPG-based approach and the reflex-based one. The former approach usually considers voluntary oscillations of neural circuits, that is, CPGs, and the output of these circuits triggers locomotion cycles. Because these behaviors are found in the spinal cord of vertebrate animals and in ganglions in invertebrates [75.64], this approach has been very popular in the bio-inspired robotics. In contrast, the reflex-based approach does not incorporate intrinsic oscillators and generate periodic behavior as a chain of reflex-mediated events. While conceptually different, most of the CPG-based approach considers reflexes in the neural processes; thus these two approaches are often overlapping and reflex-based approaches can be seen as a subset of CPG-based approaches.

One of the pioneering works in the reflex-based approach was based on the neural circuits underlying walking identified in stick insects [75.65, 66]. In this study, it was identified that a series of reflexes for each leg use information related to leg postures and ground contact to generate movements. Coordination between legs (i. e., specific gaits) is obtained with direct neural couplings between individual legs circuits and also through mechanical couplings (e.g., the movement of one limb affecting the load on other limbs). This leads to a decentralized control mechanism, similar in spirit to those developed in behavior-based robotics, that has been validated on simulated and real hexapod robots [75.65, 67].

The reflex-based approach was also investigated in human walking, in which a series of neuromechanical models were developed to demonstrate how the combination of muscle properties and low-level reflexes can lead to stable locomotion in simulated bipeds [75.68, 69]. In particular, Geyer and Herr [75.69] present a simulated bipedal walker which manages to walk in the sagittal plane and to be stable against slight slopes. This model captures principles of neuromuscular feedbacks and predicts muscle activation patterns observed in leg muscles. Similar reflex-based controllers (without muscle models but with simulated synaptic plasticity) have successfully been ported to real robots such as the Runbot [75.60] and the dynamic walkers reported in [75.37].

One of the first examples of the CPG approach has been done in simulation by *Taga* and colleagues [75.70, 71]. They developed a series of 2-D models of biped locomotion that combine a simple musculoskeletal model with a CPG modeled as a system of coupled *Matsuoka* oscillators [75.72]. The work showed how bidirectional couplings between the CPG and the musculoskeletal model could lead to entrainment (i. e., frequency locked regimes) between the two as well as to robust locomotion. Since then a large number of CPG-based controllers have been implemented in robots for different types of locomotion. Examples include hexapod and octopod robots [75.73–75] (see also Robot Roach VIDEO 112), swimming robots [75.76–78] (see also Salamandra Robotica VIDEO 113), quadruped robots [75.57, 79, 80], and biped robots [75.81–85].

As discussed in [75.64], a CPG-based approach has several interesting properties:

i) Stable limit cycle behavior that provides robustness against perturbations.
ii) Suitability for a distributed implementation.
iii) Possibility to modulate gaits with a few control parameters.
iv) Integration of sensory feedback signals in order to obtain mutual entrainment between the CPG and the mechanical body.
v) Suitable substrate for learning and optimization algorithms. These properties were particularly difficult to investigate by using animals; hence the bio-inspired robotics has provided significant contributions to the nature of motion control in biological systems.

75.3.3 Bio-Inspired Navigation

Biological systems use a variety of cognitive processes for their navigation in complex environment: it is known, for example, that animals use both proprioceptive and exteroceptive receptors for sensing environments; the obtained sensory information is passed to massively parallel processes distributed over many hierarchical levels in central nervous systems; animals' perception of the world is coordinated with low-level sensory-motor processes; and in addition to these mechanisms, long-term planning and learning processes are continuously running to achieve more advanced tasks such as goal-directed navigation. In order to tackle such a complex problem of animals' navigation, bio-inspired robotics also provided a set of effective tools to apply the synthetic methodology some of which are outlined in this subsection.

Sensor Morphology and Sensory-Motor Coordination

A significant number of researchers in bio-inspired robotics have been working on relatively simple animals such as insects because their central nervous systems are far more tractable than other animals. Despite the simplicity of their brains, insects are incredible navigators being capable of avoiding obstacles while running or flying with enormous speed, recognizing landmarks in unstructured environment, and traveling long distance for foraging. Moreover, some of the social insects can even learn to go back to their own nests, and communicate with co-workers for efficient *community management*. Although biologists have been investigating these fascinating animals for centuries, there are still a number of issues that are not fully clarified yet, and among others, robotics platforms were used to investigate the mechanisms in which physical system–environment interactions play central roles [75.86].

One of the most successful case studies in bio-inspired navigation research was on the mechanisms of sensory-motor coordination in flying insects such as flies and bees. These insects are known to rely on visual sensory information, more specifically, optic flow to detect ego motions, stabilize body posture, measure distance to various objects and landing spots, and track traveling distance, for example. While the visual information processing is usually regarded as computationally expensive, many insects, which have very limited computational resources, make use of this modality to achieve these behavioral functions. The underlying mechanisms are found in the *hardware setups* of animals, in which sensor morphology (i. e., how receptors are distributed) and low-level sensory information processing are exploited in the coordination of sensory-motor processes [75.87]. More specifically, the photoreceptors of these insects are usually distributed to almost all directions which give rise to surprisingly informative stimuli about the environment and ego motions, and low-level neural circuits are configured such that extremely low-processing power is necessary. To test these hypotheses, a number of robotic platforms were developed and tested previously, which showed the feasibility of these mechanisms such as the optic flow to detect nearby objects [75.88], visual odometry [75.89], flight altitude [75.90], and flight stabilization [75.91].

Technological advances are essential to gain additional insights into the complex sensory-motor processes in the animals. At the beginning of the investigations, many researchers developed omni-directional vision based on specifically shaped mirrors attached to regular cameras, while recently more advanced technologies are being developed to flexibly adjust photoreceptors [75.92]. Neuromorphic engineering also provides an additional enabling technology to explore physical foundations of biological nervous systems [75.93, 94]. Neuromorphic silicon retinas are, unlike conventional visual sensors, able to process sensory information extremely fast and computationally less demanding owing to the event driven and asynchronous processing architectures, while keeping sensitivity very high (i. e., the receptors can be sensitive in very dark environments as well as in a very bright one, [75.95]). With the technological progress, we will be able to reproduce more precise landscape of the world from insects' viewpoint for more comprehensive investigation of bio-inspired navigation.

Goal-Directed Navigation

Compared to reflexive behaviors, goal-directed ones are significantly more complex where much less is known even in biology. In nature, goal-directed behaviors such as navigation to a nest from a distant location require learning of routes and locations, short- and long-term memories, episodic memories, while flexibly adapting to unstructured and often dynamically changing environments. The underlying mechanisms are related to many different locations in the central nervous systems and they vary one species to another, thus the ongoing researches are essentially driven on the basis of the important findings in biology, rather than developing a unified and generalized framework.

One of the representative case studies on bio-inspired goal-directed navigation was again conducted in relation to insect behaviors (Fig. 75.8): some social insects such as desert ant Cataglyphis are known to exhibit the so-called *visual homing* behaviors, in which the animals go back to their nests by using visual cues nearby [75.96]. These insects usually walk randomly when searching for food sources, while they go back straight to the nest by using visual cues. Although the neural basis of these behaviors is not yet identified, the biologists argue that an abstract model, the so-called *average landmark vector* method, explain the insects' behavior fairly accurately. Here it is assumed that insects know the global orientation in the world, and every once in a while, they perceive the direction of foraging behavior stored as vector information. Over time, the animals sum up the vectors so that they can keep track on the direction to the nest while randomly search for the food sources. The biologists have been exploring these behaviors for decades, and the accumulated knowledge and hypothetical models were implemented and tested in physical robot platforms. Unlike most of the simulation experiments, the implementation to the robots helped to test the hypothesis in the real-world desert environment [75.96], or physically implemented in an analog circuitry (see also multimedia material of Analog Robot navigation in VIDEO 242; [75.97]).

A significantly more challenging problem is to identify the mechanisms of goal-directed behaviors in more complex animals, especially in mammals. There

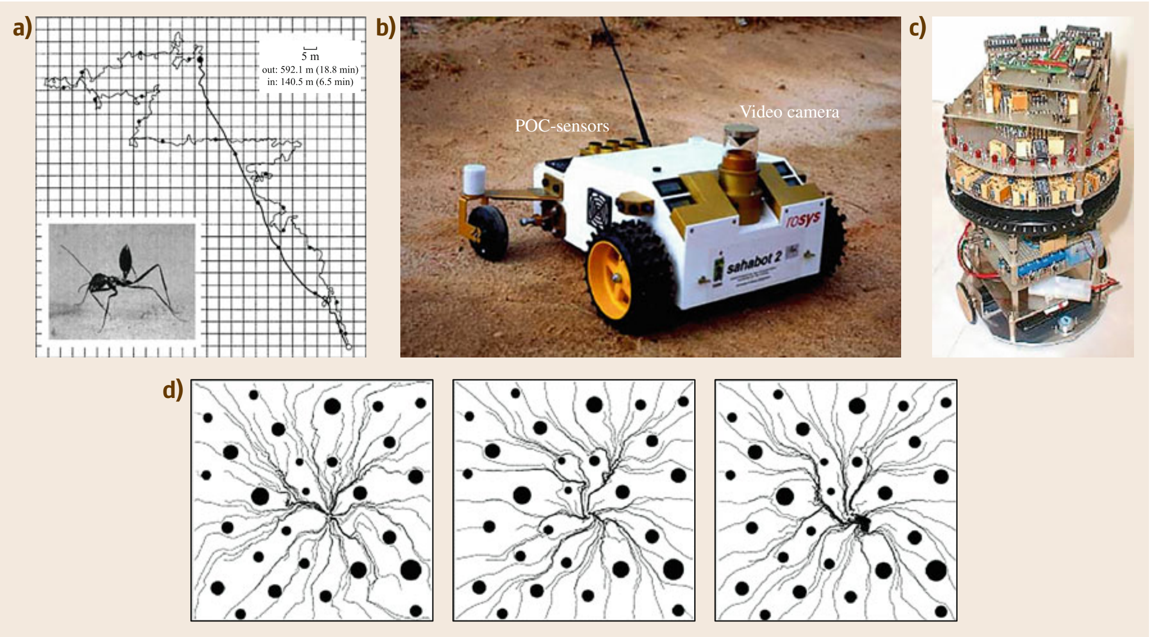

Fig.75.8a–d Visual homing of insect-inspired robots. **(a)** An result of navigation experiment of desert ant Cataglyphis. **(b)** A mobile robot Sahabot II that was developed to investigate navigation mechanisms of Cataglyphis. The robot is equipped with an omni-directional camera and a digital compass that can be used for the bio-inspired landmark navigation (after [75.96]). **(c)** A fully analog implementation of the visual homing algorithm. **(d)** Simulation results of visual homing algorithm (after [75.97])

is a large body of literature about this issue including cognitive science and brain science, but one of the most prominent contributions of robotic platforms in this research area was to explore neural dynamics during physical system–environment interactions. The research was originally motivated by a discovery in physiology such as the so-called place cells, i. e., a group of neurons in hippocampus exhibit unique behaviors whenever the animal is in a specific location in an environment [75.98]. This hard evidence in neuroscience has been widely used to analyze how brains function in the context of spatial cognition and navigation in general, including those investigating computational neuroscience and bio-inspired robotics. Essentially, it is still a challenge to explain the behaviors of place cells because they involve sensory-motor activities as well as temporal changes of neural activities (i. e., learning of sensory motor activities) thus a synthetic methodology is extremely helpful. So far it has been shown that the computational models of hippocampus were implemented onto some mobile robot platforms to replicate the behaviors of place cells in navigation tasks [75.99, 100] as well as some more complex goal-oriented behaviors and learning [75.101].

75.4 Landscape of Bio-Inspired Robotics Research and Challenges

So far we introduced only a few representative and ongoing case studies of bio-inspired robotics research, but there are many other active topic areas in the field. Although many of these studies are covered also in the other chapters of this handbook, this section provides a brief overview of the relevant topics in which robotic technologies are being used as scientific tools for biology.

75.4.1 Bio-Inspired Climbing

When legged systems are reduced down to smaller scales, adhesion forces become more dominant than the gravitational, and for this reason, the small-sized animals in nature such as insects, amphibians, and lizards tend to climb terrains rather than walk on level grounds. While the governing physics in the climbing

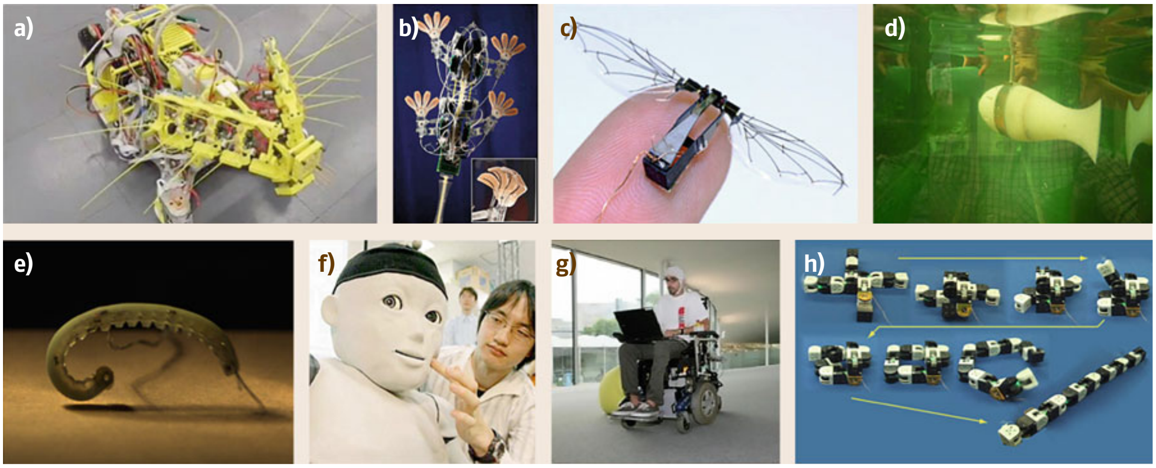

Fig. 75.9a–h Examples of recent bio-inspired robots. **(a)** A mobile robot that uses active whisker arrays for navigation (after [75.102]). **(b)** A climbing robot based on feet made of dry adhesives (after [75.103]). **(c)** Micro robot for flapping flight developed by the micro-fabrication techniques (after [75.104]). **(d)** A fish-like swimming robot that exploits soft continuum body structure (after [75.105]). **(e)** A worm-like robot that exhibit rolling-locomotion of soft body structure (after [75.106]). **(f)** A humanoid robot that is equipped with soft skin for interactions with human partners (after [75.107]). **(g)** A wheel-chair controlled by brain signals of the user (after [75.108]). **(h)** Self-reconfigurable robot that is capable of autonomously changing its own body structure (after [75.109])

locomotion is different from that of gravity-oriented legged locomotion, robotic platforms are also useful because the dynamics during the locomotion is similarly complex. One of the most representative case studies in this line of research was the use of dry adhesives in climbing robots that are inspired from geckos. Many research topics focused on the fabrication techniques of micro hair-like structures that can generate adhesive forces for a series of small-sized robots (Fig. 75.9b, [75.103, 110]). Similarly a few other approaches were also proposed to explore the different climbing strategies of animals including the use of material-dependent adhesion [75.111], rough-surface locomotion by using feet with micro spine structures [75.112, 113], and climbing strategy based on force closure of relatively long legs [75.114]. There still exist many challenges in fabrication techniques of micro structures in order to replicate the sophisticated climbing mechanisms of animals, which requires continuing close collaborations between researchers in biology and robotics.

75.4.2 Flapping Flight and Swimming Mechanisms

Another complex, yet popular, dynamics used in animal kingdom is fluid/aerodynamics that are typically observed in flying and swimming systems. Fluid/aerodynamics are also dynamics difficult to model and simulate thus robotic platforms are intensively employed for exploring underlying mechanisms [75.115, 116]. As is the case of walking and running on land, mechanical dynamics also play an important role in flying and swimming locomotion and a number of underactuated robots were developed to understand the nature of locomotion in fluid Fig. 75.9d [75.105, 117]. As the microfabrication techniques evolved in the recent years, roboticists and biologists also started collaborating to investigate small-sized flying robots (Fig. 75.9c, [75.104]; Chap. 26).

75.4.3 Artificial Hands, Haptics, and Whiskers

Haptic perception is known to be one of the most important sensor modalities in biological systems, although the biological nature is far from a comprehensive understanding because animals make use of complex sensory-motor interactions for the purpose of tactile sensing [75.118, 119]. Haptic sensing can be defined as sensing of mechanical environment through *touch* although there are many different variations in nature including tactile sensing through fingers and skins [75.119], active whisking (Fig. 75.9a) [75.102], or more specifically targeted sensing such as slippage detection [75.120]. Exploration on haptic technologies is also crucial in this research area as the biological tactile sensing involves an enormous number of mechanoreceptors each of which has a large sensitivity range. Currently, a number of researchers are actively investigating technological solutions through haptic devices and soft and stretchable electronics for tactile sensing [75.121, 122].

75.4.4 Self-Reconfigurable and Evolutionary Robotics

Animals' adaptivity in nature relies significantly on their capability of changing their body sizes and structures. Animals are, for example, able to start their lives smaller and gradually grow larger and more complex; they are able to self-repair or regenerate when encountering failures in body parts; and muscles and skins are able to strengthen themselves if necessary [75.123]. Synthetic methodology has also been employed to investigate these fascinating capabilities of biological systems by using, for example, modular robots Fig. 75.9h [75.109, 124, 125], redundant body structures for snake-like motion control [75.126, 127], and self-repair and self-assembly of structures [75.128, 129]. Due to the technological limitations, many researchers take advantage of simulation-based methods to explore the ontogenetic and evolutionary processes to uncover the characteristics of optimization strategies in nature [75.19, 20, 130].

75.4.5 Bio-Inspired Soft Robots

Unlike the conventional robots that are usually made of rigid materials articulated into discrete pieces, animals' body structures mostly consist of soft, continuum, and elastic components such as muscles, tendons, skins, organs surrounded by smooth membrane [75.1]. Recently, there has been an increasing interest in the use of soft deformable materials in robotic systems to enhance capabilities of, for example, soft locomotion [75.106, 131] (VIDEO 109 shows and example of soft robot locomotion), manipulation [75.132, 133], shape adaptation [75.134], and soft human–robot interactions [75.63]. Despite its demand in the robotics and biological studies, there are still a number of technological challenges in this field such as soft actuation and sensing [75.135], simulation of soft deformable structures [75.136], and control of flexible continuum bodies [75.137].

75.4.6 Neuroprosthetics and Social Interactions

As we develop more technological components compatible to biological systems, there are more possibilities to implant artificial devices into biological bodies. Although most of the case studies in this research area aim at bio-medical applications as exemplified by visual/auditory prosthetics, pain relief, and motor prosthetics, there are also intensive investigations on the use of prosthetic devices to gain additional insights into the nature of motion control [75.108, 138] and perception [75.139]. There is also an increasing interest in the use of robotic platforms in the studies of social interactions where robots are used to study communications with humans [75.107] and the other animals [75.140].

75.5 Conclusion

This chapter introduced a class of bio-inspired robotics research that is specifically targeted to deepen our understanding of biological systems. Through the representative case studies, we explained how bio-inspired robotics research can be useful not only for developing innovative robots, but also for exploring uncovered challenges in biology by employing the understanding-by-building approach. There are, however, a set of important concepts that need to be considered for successful collaborations between robotics and biology. Specifically:

1. It is necessary to take the similarities and differences in robots and animals into account.
2. There are different goals and methods to develop models of biological systems.
3. The use of robots as a scientific tool has both advantages and disadvantages.
4. There are types of hypotheses in biology that bio-inspired robotics can be particularly beneficial for.

And finally, we also introduced a concise landscape of trends and challenges in bio-inspired robotics. As mentioned earlier, the field of bio-inspired robotics is very broad, and the outline introduced in this chapter is by no means complete. For example, although this chapter only focused on the types of research which contribute to biological studies, there is a large body of the literature on *bio-inspired robotic applications* which are mostly ignored in this chapter. The interested readers should refer to the other chapters in this handbook as well as the other review articles in the field. Also, there are significantly more case studies available in literature which reported on the different species or the other aspects of animals which were summarized in [75.15, 18, 64].

Video-References

VIDEO 109 Dynamic rolling locomotion of GoQBot
available from http://handbookofrobotics.org/view-chapter/75/videodetails/109

VIDEO 110 JenaWalker – Biped robot with biologically-inspired bi-articular springs
available from http://handbookofrobotics.org/view-chapter/75/videodetails/110

VIDEO 111 MIT Compass Gait Robot – Locomotion over rough terrain
available from http://handbookofrobotics.org/view-chapter/75/videodetails/111

VIDEO 112 RobotRoach with adaptive gait pattern variations
available from http://handbookofrobotics.org/view-chapter/75/videodetails/112

VIDEO 113 Salamandra Robotica II – Swimming to walking transition
available from http://handbookofrobotics.org/view-chapter/75/videodetails/113

VIDEO 242 Analog Robot
available from http://handbookofrobotics.org/view-chapter/75/videodetails/242

References

75.1 R. Pfeifert, M. Lungarella, F. Iida: The challenges ahead for bio-inspired 'soft' robotics, Communications ACM **55**(11), 76–87 (2012)

75.2 G. Becky: *Autonomous Robots* (MIT Press, Cambridge 2001)

75.3 W.R. Ashby: *An Introduction to Cybernetics* (Chapman Hall, London 1956)

75.4 N. Wiener: *Cybernetics, or Communication and Control in the Animal and the Machine* (MIT Press, Cambridge 1948)

75.5 O.E. Holland: Grey Walter: The pioneer of real artificial life, Proc. 5th Int. Workshop Artif. Life, ed. by C. Langton (MIT Press, Cambridge 1997) pp. 34–44

75.6 V. Braitenberg: *Vehicles: Experiments in Synthetic Psychology* (MIT Press, Cambridge 1984)

75.7 J. von Neumann: *The Theory of Self-Reproducing Automata* (Univ. of Illinois Press, Illinois 1966)

75.8 A.M. Turing: The chemical basis of morphogenesis, Philos. Trans. R. Soc. **237**(641), 37–72 (1952)

75.9 N. Nilsson: The physical symbol system hypothesis: Status and prospects, Lect. Notes Artif. Intell. **4850**, 9–17 (2007)

75.10 R. Arkin: *Behavior-Based Robotics* (MIT Press, Cambridge 1998)

75.11 R.A. Brooks: A robust layered control system for a mobile robot, IEEE Robot. Autom. **2**(1), 14–23 (1986)

75.12 R.A. Brooks: Intelligence without representation, Artif. Intell. **47**, 139–159 (1991)

75.13 R. Pfeifer, C. Scheier: *Understanding Intelligence* (MIT Press, Cambridge 2001)

75.14 M. Lungarella, G. Metta, R. Pfeifer, G. Sandini: Developmental robotics: A survey, Connect. Sci. **15**, 151–190 (2003)

75.15 R. Pfeifer, M. Lungarella, F. Iida: Self-organization, embodiment, and biologically inspired robotics, Science **318**, 1088–1093 (2007)

75.16 T.D. Johnston, L. Edwards: Genes, interactions, and the development of behavior, Psychol. Rev. **109**(1), 26–34 (2002)

75.17 R.J. Full, D.K. Koditschek: Templates and anchors: Neuromechanical hypotheses of legged locomotion on land, J. Exp. Biol. **202**, 3325–3332 (1999)

75.18 B. Webb: Can robots make good models of biological behaviour?, Behav. Brain Sci. **24**, 1033–1050 (2001)

75.19 K. Sims: Evolving 3D morphology and behavior by competition. In: *Proc. Artificial Life IV*, ed. by R. Brooks, P. Maes (MIT Press, Cambridge 1994) pp. 28–39

75.20 J. Bongard: Morphological change in machines accelerates the evolution of robust behavior, Proc. Natl. Acad. Sci. USA **108**(4), 1234–1239 (2011)

75.21 C.G. Langton: *Artificial Life: An Overview* (MIT Press, Cambridge 1995)

75.22 A. Adamatzky, M. Komosinski: *Artificial Life Models in Hardware* (Springer, Berlin, Heidelberg 2009)

75.23 H. Lipson, J. Pollack: Automatic design and manufacture of robotic lifeforms, Nature **406**, 974–978 (2000)

75.24 G. Borelli: *De Motu Animalium* (Apud Petrum vander Aa, Cornelium Boutesteyn, Johannem de Vivie, Danielem à Gaesbeeck, Lugduni in Batavis 1685)

75.25 H. Miura, I. Shimoyama: Dynamic walk of a biped, Int. J. Robotics Res. **3**(2), 60–74 (1984)

75.26 M. Vukobratovic, B. Borovac: Zero-moment point – Thirty years of its life, Int. J. Humanoid Robotics **1**(1), 157–174 (2004)

75.27 M. Raibert: *Legged Robots that Balance* (MIT Press, Cambridge 1987)

75.28 R. Blickhan, A. Seyfarth, H. Geyer, S. Grimmer, H. Wagner, M. Guenther: Intelligence by mechanics, Philos. Trans. R. Soc. A **365**(1850), 199–220 (2007)

75.29 I.E. Brown, G.E. Loeb: A reductionist approach to creating and using neuromusculoskeletal models. In: *Biomechanical and Neurological Control of Posture and Movements*, ed. by P.E. Winters (Springer, New York 2000) pp. 148–163

75.30 T.A. McMahon: *Muscles, Reflexes, and Locomotion* (Princeton Univ. Press, Princeton 1984)

75.31 S. Yakovenko, V. Gritsenko, A. Prochazka: Contribution of stretch reflexes to locomotor control: a modeling study, Biol. Cybern. **90**(2), 146–155 (2004)

75.32 G. Orlovsky, G.N. Orlovskii, S. Grillner: *Neuronal Control of Locomotion From Mollusc to Man* (Oxford Univ. Press, Oxford 1999)
75.33 M. Bear, M. Paradiso, B.W. Connors: *Neuroscience: Exploring the Brain* (Lippincott Williams and Wilkins, Baltimore 2006)
75.34 F. Asano, M. Suguro: Limit cycle walking, running, and skipping of telescopic-legged rimless wheel, Robotica **30**(6), 989–1003 (2012)
75.35 F. Iida, R. Tedrake: Minimalistic control of biped walking in rough terrain, Auton. Robots **28**(3), 355–368 (2010)
75.36 I.R. Manchester, U. Mettin, F. Iida, R. Tedrake: Stable dynamic walking over uneven terrain, Int. J. Robotics Res. **30**(3), 265–279 (2011)
75.37 S.H. Collins, A. Ruina, R. Tedrake, M. Wisse: Efficient bipedal robots based on passive-dynamic walkers, Science **307**, 1082–1085 (2005)
75.38 D. Owaki, M. Koyama, S. Yamaguchi, S. Kubo, A. Ishiguro: A 2-D passive dynamic running biped with elastic elements, IEEE Trans. Robotics **27**(1), 156–162 (2011)
75.39 M. Ahmadi, M. Buehler: Controlled passive dynamic running experiments with ARL monopod II, IEEE Trans. Robotics **22**(5), 974–986 (2006)
75.40 F. Iida, J. Rummel, A. Seyfarth: Bipedal walking and running with spring-like biarticular muscles, J. Biomech. **41**, 656–667 (2008)
75.41 J.W. Hurst, A.A. Rizzi: Series compliance for an efficient running gait: Lessons learned from the electric cable differential leg, IEEE Robotics Autom, Mag. **15**(3), 42–51 (2008)
75.42 R. Altendorfer, N. Moore, H. Komsuoglu, H.B. Brown Jr., D. McMordie, U. Saranli, R. Full, D.E. Koditschek: RHex: A biologically inspired hexapod runner, Auton. Robots **11**, 207–213 (2001)
75.43 T. McGeer: Passive dynamic walking, Int. J. Robotics Res. **9**(2), 62–82 (1990)
75.44 A. Goswami, B. Thuilot, B. Espiau: A study of the passive gait of a compass-like biped robot: Symmetry and chaos, Int. J. Robotics Res. **17**(12), 1282–1301 (1998)
75.45 D.G.E. Hobbelen, M. Wisse: Swing-leg retraction for limit cycle walkers improves disturbance rejection, IEEE Trans. Robotics **24**(2), 377–389 (2008)
75.46 J. Hass, J.M. Herrmann, T. Geisel: Optimal mass distrib- ution for passivity-based bipedal robots, Int. J. Robotics Res. **25**(11), 1087–1098 (2006)
75.47 K. Byl, R. Tedrake: Metastable walking machines, Int. J. Robotics Res. **28**(8), 1040–1064 (2008)
75.48 R.D. Gregg, M.W. Spong: Reduction-based control of three-dimensional bipedal walking robots, Int. J. Robotics Res. **29**(6), 680–702 (2010)
75.49 R.M. Alexander: Three uses for springs in legged locomotion, Int. J. Robotics Res. **9**(2), 53–61 (1990)
75.50 X. Zhou, S. Bi: A survey of bio-inspired compliant legged robot designs, Bioinspir. Biomim. **7**(4), 1–20 (2012)
75.51 J. Rummel, A. Seyfarth: Stable running with segmented legs, Int. J. Robotics Res. **27**(8), 919–934 (2008)
75.52 T.M. Kubow, R.J. Full: The role of the mechanicalvsystem in control: A hypothesis of self-stabilization in hexapedal runners, Philos. Trans. R. Soc. B **354**, 849–862 (1999)
75.53 H. Geyer, A. Seyfarth, R. Blickhan: Compliant leg behaviour explains basic dynamics of walking and running, Proc. R. Soc. B **273**, 1471–2954 (2006)
75.54 M. Reis, F. Iida: An energy efficient hopping robot based on free vibration of a curved beam, IEEE/ASME Trans. Mechatron. **19**(1), 300–311 (2013)
75.55 A.M. Grabowski, H.M. Herr: Leg exoskeleton reduces the metabolic cost of human hopping, J. Appl. Physiol. **107**, 670–678 (2009)
75.56 A.D. Kuo: Choosing your steps carefully: Trade-offs between economy and versatility in dynamic walking bipedal robots, IEEE Robotics Autom. Mag. **14**, 18–29 (2007)
75.57 A.J. Ijspeert, A. Crespi, D. Ryczko, J.M. Cabelguen: From swimming to walking with a salamander robot driven by a spinal cord model, Science **315**(5817), 1416–1420 (2007)
75.58 S. Steingrube, M. Timme, F. Wörgötter, P. Manoonpong: Self-organized adaptation of simple neural circuits enables complex robot behavior, Nat. Phys. **6**, 224–230 (2010)
75.59 T. Geng, B. Porr, F. Wörgötter: Fast biped walking with a sensor-driven neuronal controller and real-time online learning, Int. J. Robotics Res. **25**(3), 243–259 (2006)
75.60 P. Manoonpong, T. Geng, T. Kulvicius, B. Porr, F. Wörgötter: Adaptive, fast walking in a biped robot under neuronal control and learning, PLoS Comput. Biol. **3**(7), 1305–1320 (2007)
75.61 K. Narioka, K. Hosoda: Motor development of an pneumatic musculoskeletal infant robot, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2011) pp. 963–968
75.62 G.A. Pratt, M.M. Williamson: Series elastic actuators, Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (1995) pp. 399–406
75.63 A. Albu-Schaffer, O. Eiberger, M. Grebenstein, S. Haddadin, C. Ott, T. Wimbock, S. Wolf, G. Hirzinger: Soft robotics, IEEE Robotics Autom, Mag. **15**(3), 20–30 (2008)
75.64 A.J. Ijspeert: Central pattern generators for locomotion control in animals and robots: A review, Neural Netw. **21**(4), 642–653 (2008)
75.65 H. Cruse, T. Kindermann, M. Schumm, J. Dean, J. Schmitz: Walknet: A biologically inspired network to control six- legged walking, Neural Netw. **11**, 1435–1447 (1998)
75.66 V. Dürr, A.F. Krause, J. Schmitz, H. Cruse: Neuroethological concepts and their transfer to walking machines, Int. J. Robotics Res. **22**(3/4), 151–167 (2003)
75.67 K.S. Espenschied, R.D. Quinn, H.J. Chiel, R.D. Beer: Biologically-based distributed control and local reflexes improve rough terrain locomotion in a hexapod robot, Robotics Auton. Syst. **18**, 59–64 (1996)

75.68 H. Geyer, A. Seyfarth, R. Blickhan: Positive force feedback in bouncing gaits, Proc. R. Soc. B **270**, 2173–2183 (2003)

75.69 H. Geyer, H.M. Herr: A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities, IEEE Trans. Neural. Syst. Rehabil. Eng. **18**(3), 263–273 (2010)

75.70 G. Taga, Y. Yamaguchi, H. Shimizu: Self-organized control of bipedal locomotion by neural oscillators in unpredictable environment, Biol. Cybern. **65**, 147–159 (1991)

75.71 G. Taga: A model of the neuro-musculo-skeletal system for anticipatory adjustment of human locomotion during obstacle avoidance, Biol. Cybern. **78**(1), 9–17 (1998)

75.72 K. Matsuoka: Mechanisms of frequency and pattern control in the neural rhythm generators, Biol. Cybern. **56**, 345–353 (1987)

75.73 P. Arena, L. Fortuna, M. Frasca, G. Sicurella: An adaptive, self-organizing dynamical system for hierarchical control of bio-inspired locomotion, IEEE Trans. Syst. Man Cybern. B **34**(4), 1823–1837 (2004)

75.74 S. Inagaki, H. Yuasa, T. Suzuki, T. Arai: Wave CPG model for autonomous decentralized multi-legged robot: Gait generation and walking speed control, Robotics Auton. Syst. **54**(2), 118–126 (2006)

75.75 B. Klaassen, R. Linnemann, D. Spenneberg, F. Kirchner: Biomimetic walking robot scorpion: Control and modeling, Auton. Robots **41**, 69–76 (2002)

75.76 A. Crespi, A. Ijspeert: Online optimization of swimming and crawling in an amphibious snake robot, IEEE Trans. Robotics **24**(1), 75–87 (2008)

75.77 C. Stefanini, G. Orlandi, A. Menciassi, Y. Ravier, G.L. Spina, S. Grillner: A mechanism for biomimetic actuation in lamprey-like robots, Proc. 1st IEEE/RAS-EMBS Int. Conf. Biomed. Robotics Biomechatron. (2006) pp. 579–584

75.78 C. Wilbur, W. Vorus, Y. Cao, S.N. Currie: A lamprey-based undulatory vehicle. In: *Neurotechnology for Biomimetic Robots*, ed. by J. Ayers, J.L. Davis, A. Rudolph (MIT Press, Cambridge 2002)

75.79 H. Kimura, S. Akiyama, K. Sakurama: Realization of dynamic walking and running of the quadruped using neural oscillators, Auton. Robots **7**(3), 247–258 (1999)

75.80 H. Kimura, Y. Fukuoka, A.H. Cohen: Adaptive dynamic walking of a quadruped robot on natural ground based on biological concepts, Int. J. Robotics Res. **26**(5), 475–490 (2007)

75.81 J. Nakanishi, J. Morimoto, G. Endo, G. Cheng, S. Schaal, M. Kawato: Learning from demonstration and adaptation of biped locomotion, Robotics Auton. Syst. **47**, 79–91 (2004)

75.82 S. Aoi, K. Tsuchiya: Locomotion control of a biped robot using nonlinear oscillators, Auton. Robots **19**, 219–232 (2005)

75.83 G. Endo, J. Nakanishi, J. Morimoto, G. Cheng: Experimental studies of a neural oscillator for biped locomotion with QRIO, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2005) pp. 598–604

75.84 L. Righetti, A.J. Ijspeert: Programmable central pattern generators: An application to biped locomotion control, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2006) pp. 1585–1590

75.85 R. Héliot, B. Espiau: Multisensor input for CPG-based sensorymotor coordination, IEEE Trans. Robotics **24**(1), 191–195 (2008)

75.86 D. Floreano, J.C. Zufferey, M.V. Srinivasan, C. Ellington (Eds.): *Flying Insects and Robots* (Springer, Berlin, Heidelberg 2009)

75.87 N. Franceschini, J.M. Pichon, C. Blanes: From insect vision to robot vision, Philos. Trans. R. Soc. B **337**, 283–294 (1992)

75.88 J.C. Zufferey, D. Floreano: Fly-inspired visual steering of an ultralight indoor aircraft, IEEE Trans. Robotics **22**(1), 137–146 (2006)

75.89 F. Iida: Biologically inspired visual odometer for navigation of a flying robot, Robotics Auton. Syst. **44**(3/4), 201–208 (2003)

75.90 M.V. Srinivasan, S.W. Zhang, J.S. Chahl, E. Barth, S. Venkatesh: How honeybees make grazing landings on flat surfaces, Biol. Cybern. **83**, 171–183 (2000)

75.91 S. Viollet, N. Franceschini: Aerial minirobot that stabilizes and tracks with a bio-inspired visual scanning sensor. In: *Biorobotics. Methods and Applications*, ed. by B. Webb, T. Consi (MIT Press, Cambridge 2001) pp. 67–83

75.92 M. Dobrzynski, R.P. Camara, D. Floreano: Vision Tape –A flexible compound vision sensor for motion detection and proximity estimation, IEEE Sens. J. **12**(5), 1131–1139 (2012)

75.93 C. Eliasmith, C.H. Anderson: *Neural engineering: Computation, Representation, and Dynamics in Neurobiological Systems* (MIT Press, Cambridge 2004)

75.94 S.C. Liu, T. Delbruck: Neuromorphic sensory systems, Curr. Opin. Neurobiol. **20**, 1–8 (2010)

75.95 R. Berner, T. Delbruck: Event-based pixel sensitive to changes of color and brightness, IEEE Trans. Circuits Syst. I **58**(7), 1581–1590 (2011)

75.96 D. Lambrinos, R. Möller, T. Labhart, R. Pfeifer, R. Wehner: A mobile robot employing insect strategies for navigation, Robotics Auton. Syst. **30**(1/2), 39–64 (2000)

75.97 R. Möller: Insect visual homing strategies in a robot with analog processing, Biol. Cybern. **83**(3), 231–243 (2000)

75.98 E. Moser, E. Kropff, M. Moser: Place cells, grid cells, and the brain's spatial representation system, Annu. Rev. Neurosci. **31**, 69–89 (2008)

75.99 J.L. Krichmar, D.A. Nitz, J.A. Gally, G.M. Edelman: Characterizing functional hippocampal pathways in a brain-based device as it solves a spatial memory task, Proc. Natl. Acad. Sci. USA **102**, 2111–2116 (2005)

75.100 M.J. Milford, J. Wiles, G.F. Wyeth: Solving navigational uncertainty using grid cells on robots, PLoS Comput. Biol. **6**(11), e1000995 (2010)

75.101 G. Edelman: Learning in and from brain-based devices, Science **318**, 1103–1105 (2007)
75.102 T.J. Prescott, M.J. Pearson, B. Mitchinson, T. Pipe: Whisking with robots: From rat vibrissae to biomimetic technology for active touch, IEEE Robotics Autom. Mag. **16**, 42–50 (2009)
75.103 S. Kim, A. Asbeck, M. Cutkosky, W. Provancher: SpinybotII: Climbing hard walls with compliant microspines, Proc. 12th Int. Conf. Adv. Robotics (ICAR) (2005) pp. 601–606
75.104 R.J. Wood: The first biologically inspired at-scale robotic insect, IEEE Trans. Robotics **24**(2), 341–347 (2008)
75.105 T. Salumäe, M. Kruusmaa: A flexible fin with bio-inspired stiffness profile and geometry, J. Bionic Eng. **8**(4), 418–428 (2011)
75.106 H.T. Lin, G.G. Leisk, B. Trimmer: GoQBot: A caterpillar-inspired soft-bodied rolling robot, Bioinspir. Biomim. **6**, 026007 (2011)
75.107 M. Asada, K. Hosoda, Y. Kuniyoshi, H. Ishiguro, T. Inui, Y. Yoshikawa, M. Ogino, C. Yoshida: Cognitive developmental robotics: A survey, IEEE Trans. Auton. Mental Dev. **1**(1), 12–34 (2009)
75.108 T. Carlson, J.D.R. Mill: Brain-controlled wheelchairs: A robotic architecture, IEEE Robotics Autom, Mag. **20**(1), 65–73 (2013)
75.109 S. Murata, H. Kurokawa: Self-reconfigurable robots, IEEE Robotics Autom, Mag. **14**(1), 71–78 (2007)
75.110 M.R. Cutkosky, S. Kim: Design and fabrication of multi-material structures for bioinspired robots, Philos. Trans. R. Soc. **367**, 1799–1813 (2009)
75.111 O. Unver, M. Sitti: Tankbot: A palm-size, tank like climbing robot on rough and smooth surfaces, Int. J. Robotics Res. **29**(14), 1761–1777 (2010)
75.112 A.T. Asbeck, S. Kim, M.R. Cutkosky, W.R. Provancher, M. Lanzetta: Scaling hard vertical surfaces with compliant microspine arrays, Int. J. Robotics Res. **25**(12), 1165–1179 (2006)
75.113 M.J. Spenko, G.C. Haynes, J.A. Saunders, M.R. Cutkosky, A.A. Rizzi, R.J. Full, D.E. Koditschek: Biologically inspired climbing with a hexapedal robot, J. Field Robotics **25**(4/5), 223–242 (2008)
75.114 T. Lam, Y. Xu: Climbing strategy for a flexible tree climbing robot Treebot, IEEE Trans. Robotics **27**(6), 1107–1117 (2011)
75.115 M.S. Triantafyllou, G.S. Triantafyllou: An efficient swimming machine, Sci. Am. **272**(3), 40–48 (1995)
75.116 M.H. Dickinson, C.T. Farley, R.J. Full, M.A. Koehl, R. Kram, S. Lehman: How animals move: An integrative view, Science **288**(5463), 100–106 (2000)
75.117 G.V. Lauder, E.J. Anderson, J. Tangorra, P.G. Madden: Fish biorobotics: Kinematics and hydrodynamics of self-propulsion, J. Exp. Biol. **210**(16), 2767–2780 (2007)
75.118 R. Fearing, J. Hollerbach: Basic solid mechanics for tactile sensing, Int. J. Robotics Res. **1**, 266–275 (1984)
75.119 V. Hayward, O.R. Astley, M. Cruz-Hernandez, D. Grant, G. Robles-De-La-Torre: Haptic interfaces and devices, Sens. Rev. **24**(1), 16–29 (2004)
75.120 D. Gunji, Y. Mizoguchi, S. Teshigawara, A. Ming, A. Namiki, M. Ishikawaand, M. Shimojo: Grasping force control of multi-fingered robot hand based on slip detection using tactile sensor, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2008) pp. 2605–2610
75.121 T. Someya, Y. Kato, T. Sekitani, S. Iba, Y. Noguchi, Y. Murase, H. Kawaguchi, T. Sakurai: Conformable, flexible, large-area networks of pressure and thermal sensors with organic transistor active matrixes, Proc. Natl. Acad. Sci. USA **102**, 12321–12325 (2005)
75.122 G. Cannata, M. Maggiali, G. Metta, G. Sandini: An embedded artificial skin for humanoid robots, Int. Conf. Multi-Sensor Fusion Integr. (2008) pp. 434–438
75.123 S.F. Gilbert: *Developmental Biology* (Palgrave Macmillan, London 2010)
75.124 F. Hara, R. Pfeifer (Eds.): *Morpho-Functional Machines: The New Species: Designing Embodied Intelligence* (Springer, Berlin, Heidelberg 2003)
75.125 M. Yim, W.M. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, G.S. Chirikjian: Modular self-reconfigurable robot systems: Challenges and opportunities for the future, IEEE Robotics Autom, Mag. **14**(1), 43–52 (2007)
75.126 S. Hirose: *Biologically inspired robots: Snake-like locomotors and manipulators* (Oxford Univ. Press, Oxford 1993)
75.127 T. Kano, T. Sato, R. Kobayashi, A. Ishiguro: Local reflexive mechanisms essential for snakes' scaffold-based locomotion, Bioinspir. Biomim. **7**, 046008 (2012)
75.128 P.J. White, K. Kopanski, H. Lipson: Stochastic self-reconfigurable cellular robotics, Proc. IEEE Int. Conf. Robotics Autom. (ICRA) (2004) pp. 2888–2893
75.129 E. Klavins, R. Ghrist, D. Lipsky: A grammatical approach to self-organizing robotic systems, IEEE Trans. Autom. Control **51**(6), 949–962 (2006)
75.130 S. Nolfi, D. Floreano: *Evolutionary Robotics. The Biology, Intelligence, and Technology of Self-Organizing Machines* (MIT Press, Cambridge 2000)
75.131 S. Seok, C.D. Onal, K.J. Cho, R.J. Wood, D. Rus, S. Kim: Meshworm: A peristaltic soft robot with antagonistic nickel titanium coil actuators, IEEE/ASME Trans. Mechatron. **18**, 1485–1497 (2013)
75.132 D. Trivedi, C.D. Rahn, W.M. Kier, I.D. Walker: Soft robotics: Biological inspiration, state of the art, and future research, Appl. Bionics Biomech. **5**(3), 99–117 (2008)
75.133 F. Ilievski, A.D. Mazzeo, R.F. Shepherd, X. Chen, G.M. Whitesides: Soft robotics for chemists, Angew. Chem. Int. Ed. **50**, 1890–1895 (2011)
75.134 L. Brodbeck, F. Iida: Enhanced robotic body extension with modular units, Proc. 2012 IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS) (2012) pp. 1428–1433
75.135 A.T. Conn, J.M. Rossiter: Towards holonomic electro-elastomer actuators with six degrees of

freedom, Smart Mater. Struct. **21**, 035012–035020 (2012)
75.136 J. Rieffel, D. Knox, S. Smith, B.A. Trimmer: Growing and evolving soft robots, Artif. Life **20**(1), 143–162 (2014)
75.137 C. Laschi, B. Mazzolai, V. Mattoli, M. Cianchetti, P. Dario: Design of a biomimetic robotic octopus arm, Bioinspir. Biomim. **4**, 1–8 (2009)
75.138 A.B. Schwartz, X.T. Cui, D.J. Weber, D.W. Moran: Brain-controlled interfaces: Movement restoration with neural prosthetics, Neuron **52**(1), 205–220 (2006)
75.139 J.E. O'Doherty, M.A. Lebedev, K.Z. Zhuang, S. Shokur, H. Bleuler, M.A.L. Nicolelis: Active tactile exploration enabled by a brain-machine-brain interface, Nature **479**, 228–231 (2011)
75.140 J. Halloy, G. Sempo, G. Caprari, C. Rivault, M. Asadpour, F. Tache, I. Said, V. Durier, S. Canonge, J.M. Ame, C. Detrain, N. Correll, A. Martinoli, F. Mondada, R. Siegwart, J.L. Deneubourg: Social integration of robots into groups of cockroaches to control self-organized choices, Science **318**(5853), 1155–1158 (2007)