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Biologically Inspired Robots

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1. Introduction

The idea of building machines that emulate features of animals that we see around us has a long history. Leonardo da Vinci's drawings of machines that fly like birds are one familiar example. It was not until the middle of the 19th century, however, that scientific knowledge had advanced enough for realistic and realizable plans for such machines to be made (Raibert, 1986) and truly successful attempts to make walking or crawling robots proliferated only in the last few decades of the 20th century (e.g., Raibert, 1990).

In the sense that any machine that swims, flies, or walks can be said to be inspired by fish, birds, or legged animals, every mobile robot that employs one of these means of locomotion can be said to be biologically inspired. However, the term biologically inspired and the current concept of biologically inspired robotics originated in the last few decades of the 20th century. The first use of the phrase in the title of a journal article appears to have been by Beer et al. (1997). In this article, Beer and his colleagues make a distinction between merely emulating some general feature of an animal like legs or wings and a more considered approach in which specific structural or functional elements of particular animals is emulated in hardware or software.

Because animals are both structurally and functionally complex, it is obvious that a complete reproduction of any animal in hardware and software is not possible. Hence, there is some debate among bioroboticists about where to draw the line. Some researchers take the approach of Ritzmann and colleagues (Ritzmann et al., 2000), who suggested that as many features of an animal should be incorporated into a robot as possible, even if the functional advantage of any particular feature is not clear (e.g., Cham et al., 2004; Dillmann et al., 2007). In recent years, this approach has sometimes been called biomimetic robotics (e.g., Ayres & Witting, 2007). The argument is that many of these features actually do confer useful attributes to the robot even if that usefulness is not immediately apparent. Other researchers take a more conservative approach, even arguing that including too many animal-like features into a robot can impair performance (e.g., Yoneda & Ota, 2003).

Biorobotics has a second element as well. In addition to arguing that using biological principles as a source of inspiration for the construction of robots, some researchers have argued that studying robots can advance biologists' knowledge and understanding of those same biological principles (Beer et al., 1998; Ritzmann et al., 2000; Webb, 2006). The idea is that any attempt to implement in hardware and software specific features of a real animal can only improve our understanding of those features because such an attempt will immediately expose any part of our understanding that is incomplete or that when

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implemented does not lead to a level of performance that is expected. The discussion paper by Webb (2001a) and the resulting commentaries (see discussion of them by Webb, 2001b) is probably the best single source for an introduction to this approach and the response of the biological and engineering communities to it.

Whether approached from an engineering or a biological perspective, there is no doubt that by whatever term one chooses to characterize it, bioinspired engineering, biorobotics, biological inspiration, or biomimetics, the fusion of biology and engineering is emerging as a discipline in its own right. The appearance of semi-popular works (e.g., Paulson, 2004) and papers appearing in non-traditional journals (e.g., Delcomyn, 2004) also attests to the growing awareness of the field. This does not even include the more than 1.5 million hits one obtains by conducting a Google search on the phrase "walking robot" or the roughly 61,400 hits for pages with images of robots with legs as of June, 2007. Considering only the research literature, a search of the ISI Web of Knowledge database reveals that from 2000 to 2004, there were an average of 9.2 papers per year on mobile robotic machines that listed biological inspiration or variants thereof as a key phrase. In 2005, the number jumped to 16, an increase of over 70%, and in 2006, there were 30, an additional increment of more than 85%. Though not large, this is nevertheless a field worth paying attention to.

2. Bioinspiration as a Means of Improving Robotic Performance

2.1 Animal locomotion and its performance features

Two words encapsulate what engineers find attractive about the walking and running of animals – speed and agility. Running speed among mammals ranges from about 8 miles per hour (mph; 12 km/hr or 3.6 meters per second) for a mouse to a top speed of about 70 mph (113 km/hr, 31 m/s) for a cheetah. Small animals like insects, of course, move much more slowly, only a few miles per hour at best. The land speed record for an insect appears to be a tiger beetle at 5.5 mph (8.8 km/hr, 2.5 m/s) (Kamoun & Hogenhout, 1996). Some cockroaches are also relatively fast, some having been clocked at about 3 mph (5.5 km/hr, 1.5 m/s; Full & Tu, 1991).

More relevant to small animals, however, is body-lengths per second, since this measure scales the speed of locomotion to the size of the animal. Cheetahs check in at about 20-29 body lengths per second. Cockroaches and mice run at about 50 to 71 body lengths per second, while the swift tiger beetle apparently tops the scale at 245 body lengths per second.

Agility is much more difficult to measure since there is no single measurement one can make that will represent it. Clearly, many animals are extraordinarily agile – think of monkeys scrambling about in the treetops or a snow leopard chasing a goat nearly full speed down a steep mountain slope. A few studies have been done on agility among insects, though measuring agility was not the purpose of the study. Frantsevich & Cruse (2005) showed that a small bug (approximately 1 cm long) is able to walk along a stick about 1 mm in diameter and when it reaches the end, smoothly turn around and walk back without falling off. A stick insect has also been shown to be able to cross a gap that is about as wide as the length of its body (Bläsing, 2006). Cockroaches are adept at climbing over obstacles that are at least as high as they are (Watson et al., 2002). Some can run over rugged surfaces containing obstacles about twice the insect's height (Full et al., 1998).

2.2 Robotic locomotion and its performance features

How do legged robots perform compared to their living counterparts? This question is not as easy to answer as one might hope since many published descriptions of such robots do not include the relevant data. It is obvious from a recent compilation of performance by Saranli et al. (2001), however, that they do not do so well by comparison. Saranli et al. (2001) give dimensions and speed performances of several walking robots, whose speeds range from about 0.02 to 1.1 meters/sec (from 0.006 to 2.5 body lengths/sec). To date, the two fastest types of legged robot seem to be robots of the Sprawl series and RHex (Figure 1). The Sprawl robots, hexapods based on the biomechanics of cockroaches, have been specifically designed to include compliant features in their six legs (Bailey et al., 2001; Cham et al., 2002; Dordevic et al., 2005; Kim et al., 2006). Recent versions can move at about 2.3 m/sec. (about 15 body lengths/sec.) even over uneven terrain (Clark & Cutkosky, 2006).

Figure 1. The hexapod robot RHex. Note that although the configuration of the body and the legs does not emulate its model organism, a cockroach, its biomechanics does incorporate the swing inverted pendulum mechanical motion that cockroaches and other insects use. (Photo provided by M. Buehler. Photo © by M. Buehler. Used by permission.)

RHex (Saranli et al., 2001) has in its latest version been clocked at over 5 body lengths per second (Weingarten et al., 2004). This robot, though not insect-like in appearance, is nevertheless designed to employ kinematic and functional features of insect locomotion. It is able to traverse rough terrain as well as stairs with risers higher than its body height (Moore & Buehler, 2001).

Although recent reports do a better job of giving specific details of a robot's physical parameters and its speed of walking, it is clear that there is still no set of tests to which engineers routinely subject their constructions in order to test performance. Not just speed of walking over a level surface, but also such parameters as minimum turning radius, steepest incline navigable, height of obstacle (relative to body height) that can be climbed over, etc., should be assessed and reported. As Delcomyn (2004) has pointed out, using such a set of tests for all walking robots would greatly advance the discipline of biorobotics.

3. Crawling Robots

3.1 Applications

Although certainly some robots are designed and built with the prime objective being research on the physical features of the robot or on the mechanisms that control it, most are conceived and built with one or more specific applications in mind. This seems to be particularly true for crawling robots. Furthermore, the great diversity of applications for which such robots are built is reflected in the great diversity of their physical structure. This structure ranges from legged robots that drag their bodies along the substrate (e.g., Voyles & Larson, 2005) to worm- or snake-like robots (Menciassi & Dario, 2003, Menciassi et al., 2006; Chernousko, 2005; Crespi et al., 2005).

Actual or suggested applications for crawling robots are as diverse as body types and include inspection and maintenance of pipelines (Bolotnik et al., 2002; Chatzakos et al., 2006; Gu et al., 2005), construction of a space array (Kaya et al., 2005), open heart surgury (Riviere et al., 2004), surveillance (Voyles & Larson, 2005), search and rescue (Wang & Appleton, 2003), and off-world exploration (Voyles & Larson, 2005).

Pipeline or tunnel inspection and maintenance is probably the most common use for crawling robots. Some robots in this category are intended simply to crawl along the exterior (Chatzakos et al., 2006) or the interior (Bolotnik et al., 2002) of a pipeline. Others are more complex, being able to alter their shapes (Wang & Appleton, 2003) in order to squeeze through broken areas or to detect the profile of a pipe in order to identify collapsed tunnels or pipes (Gu et al., 2005). Some crawling robots have no legs and are more exotic, such as a small remotely controlled robot that adheres by suction to a heart or other tissue during surgury (Riviere et al., 2004).

3.2 Features

Crawling robots slither or pull/push themselves along the surface on which they are moving and therefore need not be concerned with maintaining balance. (Although robots that move along pipes or tubes are typically referred to as crawling, some may actually support their body weight on their legs (e.g., Bolotnik et al., 2002).) Hence it is probably fair to say that there is a greater variety of means of locomotion among crawling than among walking robots.

Except for the presence of legs, there is no indication that pipe-crawling robots have been designed with any biological principles or features in mind. Most are conventional, in the sense that they typically have 6-8 legs, but a few have unusual features. Voyles & Larson (2005) have designed a small two-legged robot that can crawl by dragging its body along. Its small size will enable it to search through the rubble of collapsed buildings for survivors or to explore the rugged terrain of other planets. Not having to support its body weight on its legs means that the two "arms" can be used to manipulate objects in the environment if necessary. Wang & Appleton (2003) offer a shape-shifting robot to make it possible for the robot to squeeze through small spaces.

Most crawling robots have no legs, though some do (Matsuno et al., 2002; Voyles & Larson, 2005). Legless robots come in a variety of forms and use a variety of locomotor schemes. Some are modeled after snakes both structurally and functionally and progress by a snake-like slithering locomotion (e.g., Chernousko, 2005). Others are designed to progress more like earthworms, using peristaltic movement, a repetitive, concertena-like compression and elongation of the body, to move forward (Menciassi et al., 2006). A third type progresses like an inchworm, having sucker-like appendages at the front and back and moving forward by attaching to the substrate at the front end, pulling the body forward, then attaching at the rear, releasing the front sucker and advancing the body, and repeating the cycle (Riviere et al., 2004).

3.3 Performance and advantages

As pointed out by Saga & Nakamura (2004), snake-like or worm-like locomotion generally requires less space than does locomotion with legs because the body is elongated and does not have any projections. Hence, robots built to emulate snakes or worms have an inherent advantage over robots with legs when they must operate in close quarters. This advantage, however, is offset by rather slow forward progression. Multilink snake-like robots, for example, can travel at less than 20 cm/sec (Chernousko, 2005). Given their size (more than a meter long), this translates into less than 0.01 body lengths/sec.

Some snakes, like some other animals, are amphibious. Certainly an amphibious robot can be designed with legs or without, but an advantage of an amphibious snake-like robot is that a similar control system can be used to regulate motion in water and on land. Legged animals generally use their legs differently on land than in the water, hence adding an extra layer of complexity to any legged amphibious robot (Ijspeert et al., 2005). By using a snake model, Crespi and colleagues (Crespi et al., 2005) are able to use a single control mechanism, since the locomotion they are emulating is essentially the same on land as it is in the water.

Robots designed to emulate the peristaltic locomotion of worms can move forward using even less space than snake-like robots require (Saga & Nakamura, 2004) because there is no side-to-side motion of the body at all. The challenge for robots modelled after worms is finding an appropriate type of actuator that will impart the necessary motion to the body. Saga & Nakamura (2004) have implemented a novel approach, using a magnetic fluid whose viscosity changes with a fluctuating magnetic field inside a micro-robot. Hence, the robot can be controlled in a restricted environment from outside the robot itself. Furthermore, even though the robot requires no wires or external connection, its movements can nevertheless be precisely controlled by application of an external magnet that supplies the necessary magnetic field.

An important advantage of biomimetically designed worm-like crawling robots is their potential use in medicine. In addition to their modular nature, a feature that simplifies construction and control, the main advantage of such robots is the possibility of their use inside the human intestine or in blood vessels. For example, Menciassi and collaborators (Menciassi & Dario, 2003; Menciassi et al., 2006) have developed a robot that could in principle be used in microendoscopy, a procedure for examining for abnormalities the human intestinal tract or small tubes or ducts. The main feature of the robot is a system of microhooks on its surface, enabling it to gain traction against the smooth inner surface of any biological tube or duct. Progression is achieved through control of shape memory alloy in the robot that is deformed and then regains its original form, moving the robot forward.

An advantage of robots based on peristaltic locomotion is that they can press against the walls of the tube within which they are moving. If the robot is to be used on the exterior surface of an object, this obviously cannot be done. In these circumstances, an inchworm-like robot may be a better choice and such robots have been designed for these circumstances. For example, Rincon & Castro (2003) discuss their inchworm-like robot and its structural advantages. (It should be noted, however, that they describe as "inchwormlike" the peristaltic locomotion of an earthworm, which is not a correct usage of the term.) Riviere and colleagues (Riviere et al., 2004; Patronik et al., 2004) have used the inchworm model for their small robot that can work on the epicardium of a beating heart. The robot adheres by suction and navigates by crawling like an inchworm under control or an operating surgeon.

4. Walking Robots

4.1 Applications

Many of the applications suggested for crawling robots, such as surveillance, search and rescue, and off-world exploration, have been suggested for walking robots as well. Even endoscopic surgery, to which crawling robots might seem better suited, has been proposed as an application for a robot with legs (Urban et al., 1999). Underwater walking applications have been implemented successfully as well (Ayres, 2004).

The presence of legs does in principle add a functional capacity not generally available to crawling, legless, robots – the ability to walk up vertical surfaces. (Some snakes can actually climb trees, but climbing is not a feature of snake-like robots.) A way to grip a surface with enough force that the robot will not slip and fall is, however, not easy to devise. Most animals that can climb are either quite small (like insects) and therefore do not have much weight to support, or have claws or other special adaptations on their feet that enable them to form a firm grip on surfaces. One animal used as a model for studies of wall-climbing is the gecko. These reptiles have special pads on the soles of their feet that allow them to adhere to virtually any surface; this feature has made them attractive subjects for research on how to incorporate tight grip into a robot (Dai & Sun, 2007).

A second active area of research that is unique to robots with legs is the study of humanoid robots (e.g., Witte et al., 2004). Part of the attraction of these robots is the challenge of designing one that can walk and balance well on two legs. Although a task like ascending or descending stairs can be carried out by humans without any thought at all, it is not so easy to design a robot to do the same thing since the balance issues are significant. Another attraction is simply the challenge of building a robot that looks like a human being, and that can interact with humans. The Honda Corporation has been particularly active in this field, having designed and built a fully independent, walking humanoid robot. (Simple technical details are available at the Honda web site: http://asimo.honda.com/EducationMaterials.aspx.) An important driving force in this burgeoning field of research is the goal of building humanoid robots that can serve along with humans in ordinary workspaces or in homes. The challenges are well described in a recent review by Kemp et al. (2007). Engineers in the field generally do not use the term biomimetic in reference to their work, but any attempt to emulate the physical structure of a living organism in a robot obviously does fall into this category.

4.2 Features

A search of the ISI Web of Science database in June, 2007 using the search terms *robot* and *walking* together yielded more than 660 publications. Clearly, this is an active area of research and any brief overview of the field like this one cannot hope to be comprehensive. Here I will concentrate on features of some representative biomimetic robots that seem particularly important.

Walking or hopping robots have been made with leg numbers ranging from one to 10. Animal models for these robots include humans (Witte et al., 2004), rats (Chavarriaga et al., 2005), salamanders (Ijspeert et al., 2005), a variety of insects (ants: Goulet & Gosselin, 2005, cockroaches: Delcomyn & Nelson, 2000; Saranli et al., 2001; Nelson et al., 1999; stick insects: Dean et al., 1999), scorpions (Klaassen et al., 2002), and lobsters (Ayres & Witting, 2007). Raibert & Hodgins (1993) have developed a single-legged robot that "walks" by hopping.

Some robots are designed to reproduce the physical structure of the animal after which they are modeled (e.g., Delcomyn & Nelson, 2000; Nelson et al, 1999; Ayres & Witting, 2007; see Figure 2) but scaled up appropriately in size. The rationale for this attention to detail is that the physical structure of the animal (the differences in size, structure, and articulation with the body in the legs of cockroaches, for example) confers to it certain locomotor capabilities and that by emulating the animal's physical structure some of those capabilities will be conferred to the robot (Ritzmann et al., 2004). Other robots are built along more conventional engineering lines with legs being similar to one another and simply articulated (Dillmann et al., 2007). One hexapod robot, RHex, while not built to resemble its model organism physically, nevertheless was designed to emulate the kinamatics and dynamics of its walking (Altendorfer et al., 2001). And while most robots are built with a rigid body, some have been designed with the ability to flex or bend the body just as animals can. This feature has been shown to aid significantly in the robot's ability to climb over obstacles (Quin et al., 2003).

An important element in any walking robot is the type of actuator used to power the movements of the limbs. In early robots, the actuator of choice was generally an electrical motor (e.g., Beer et al., 1997). Later robots have used pneumatics (Nelson & Delcomyn, 2000, Quinn et al., 2001) to drive the legs or artificial muscles such as McKibbon actuators. (Klute et al., 2002), electroactive polymers (Bar-Cohen, 2003), Nitinol wire with shape memory (Safak & Adams, 2002), and other devices. The common feature of these artificial muscle devices is that they incorporate essential features of living muscle such as compliance and favorable force-velocity relationships while at the same time not consuming too much power.

No robot is of any use if it cannot walk effectively, so an appropriate method of controlling leg movements is obviously essential. Here again, a comparison of the control mechanisms used in early robots with those that are generally used today shows the influence and effectiveness of biorobotics. Even early biomimetic robots tended to be controlled in a rather rigid fashion, such that hexapod walking machines, for example, were programmed to use the typical insect tripod gait (front and rear legs on one side of the body moving together with the middle leg on the other side, and these three legs alternating their movements with the other three) at all times. More recent robots use a more flexible control system that allows independent movement of the legs of the robot when this is desirable (e.g., Arena et al., 2002, 2004), leading to a flexible determination of the appropriate gait to use in a given circumstance.

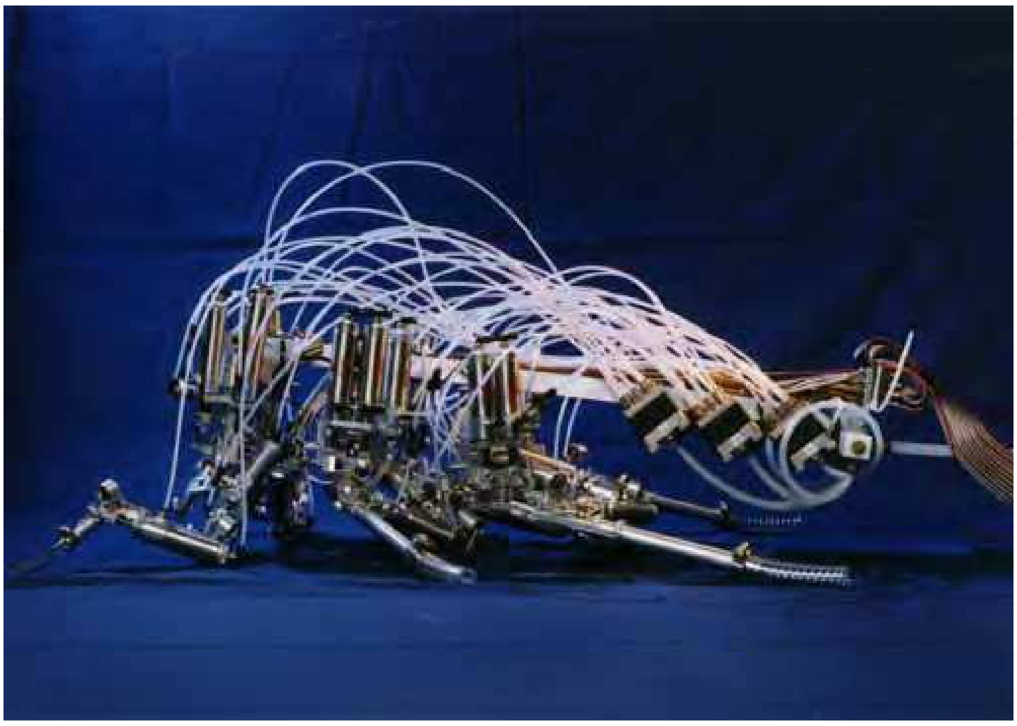

Figure 2. Robot III, a pneumatically powered hexapod modeled structurally and functionally after a cockroach. Robot III was developed at Case Western Reserve University through a long standing collaboration between Roger Quinn's Biorobotics Lab and Roy Ritzmann's neurobiology and behavior lab. Based upon biological data from James Watson, it was designed by Richard Bachmann and Gabriel Nelson with control software by Nelson. (Photo © by and used by permission of R. Quinn. From Quinn et al., 2001, Figure 2, Courtesy of Springer Verlag.)

4.3 Performance and advantages

As noted by Ritzmann et al. (2000), Cham et al. (2002), Bubic (1999) and many others, the appeal of biorobotics is the enhancement of performance that building a robot that incorporates biological features into its structural and functional organization is expected to produce. Certainly based on results as of 2007, this expectation is fully justified. The top speed of a legged robot, for example, has improved from about 2.5 body lengths/sec in 2001 (see the comparisons set out by Saranli et al., 2001) to more than 15 body lengths/sec (Clark & Cutkosky, 2006), a six-fold improvement. Furthermore, although some early walking robots could traverse a walking surface that contained narrow gaps (described in Quinn et al., 2002), they were slowed considerably or even stopped entirely by large gaps, any high barrier or other complex terrain. More recent machines, on the other hand, are able to run with good speed over complex terrain and even navigate stairs (Clark & Cutkosky, 2006; Moore & Buehler, 2001).

Significant improvements in performance are often described in papers or at conferences by comparing the performance of a new robot with its predecessors. This is certainly useful. However, another welcome trend in recent research is to compare the performance of a walking robot directly with its animal counterpart (e.g., Bailey et al., 2001; Quinn et al., 2003), something that was not usually done except in the most casual way by early workers. This can be particularly useful because it is clear from zoology that animals themselves have widely disparate abilities to move fast or to traverse rugged terrain. Hence, it can be helpful to evaluate any robot not against some absolute standard but against its animal model, suitably scaled. After all, comparing the speed of a robot to that of a cheetah is hardly useful if the objective is to make a mechanical rat.

Improvements in robotic performance have come from several different avenues of research. One of these is investigations in biomechanics. This topic has until recently been rather neglected even among biologists. Not until the seminal article by Chiel & Beer (1997), in which they pointed out the importance of kinematics and skeletomuscular mechanics to locomotion (and indeed, any behavior), did biologists who study locomotion begin to take much notice of biomechanics. In the following decade, the topic began to yield new insights into how walking is controlled in animals and the contribution of biomechanics to walking. In brief, research has shown that the skeletomuscular system of an animal acts as a kind of natural resonant system that stabilizes the body during fast locomotion. This is true for all legged animals. (See Delcomyn, 2004, for a review of the relevant insect literature, and Dickinson, et al., 2000 and Full & Farley, 2000 for a more general discussion of biomechanics and animal locomotion.)

The new appreciation for biomechanics has spilled into the field of biorobotics. Much of this biomechanical robotics work has been done using insect models. The robot RHex, in particular, has been built specifically to incorporate the spring-loaded inverted pendulum leg movements of cockroaches and other insects into its walking (Altendorfer et al., 2001; Koditschek et al., 2004). Clark & Cutkosky (2006) have shown the importance of the different sizes and shapes of the legs of insects like cockroaches, which impact the mechanics of the insect's walking. Other animals have been used as models as well, as shown by the recent work of Geng et al. (2006) on biped walking, in which they demonstrated that a stable biped walk can be mastered by a robot in part by taking the biomechanics of bipeds into account in the design of the machine.

A second important area of research that has led to better robotic performance is in the area of control. Traditional approaches to control of movement, coming as they did from the necessity to control the movements of industrial robots to a high degree of precision, involve precise calculation of intended movements (Spong & Vidyasagar, 1989). Although this approach has been applied to walking robots with some success, the method imposes a high computational load on the controller and severely limits the flexibility of the walking gaits that can be used (e.g., Pratihar et al., 2000). An alternative approach is the use of a biomimetically designed controller based on the principles of locomotor control used by animals (see Delcomyn, 1999 for an overview of the topic). A number of investigators have used the biological concept of a central pattern generator (CPG) for generation of walking patterns (e.g., Arena et al., 2002, 2004; Ayres & Witting, 2007; Collins & Richmond, 1994; Fukuoka et al., 2003). Investigators have also employed the concept of distributed control, that is, that gait is generated by an interaction of CPGs controlling different legs or even different joints of single legs, and the feedback from sensors in the legs (e.g., Beer et al., 1992;

Chiel et al., 1992; Dean et al., 1999; Kindermann, 2001). Underappreciated work by Ferrell (1995) compared the performance of various models of locomotor control.

Complementing work on biomechanics and controllers is research on actuators. Early robots used electrical motors to power movement of the legs (e.g., Quinn & Espenschied, 1993), but it was apparent from the beginning that such motors could not generate the power and speed of action that would allow robots to emulate animal walking. The problem for engineers is that muscle is compliant and has the ability to develop and release tension extremely rapidly. Both attributes feature prominently in the ability of muscle to power leg movements during walking.

Early attempts to actuate robot legs by muscle-like actuators took advantage of the principles of pneumatics. Compressed air introduced into cylinders to impart movement to pistons has compliance, an important feature of muscle. Furthermore, when pulsed, power can be controlled in ways quite similar to the ways in which muscle is controlled by the nervous system (Cocatre-Zilgien et al., 1996; Delcomyn & Nelson, 2000). In some cases, pneumatic control is used in flexible devices known as a McKibben actuators (Klute et al., 2002; Quinn et al., 2001). A significant problem with pneumatics, however, is that a robot so powered must either generate its own compressed air or be tethered via tubes to a supply, thus eliminating the possibility that the robot can be autonomous.

A number of research efforts in recent years have attempted to make alternative artificial muscles. The types of such artificial muscles include those composed of Nitinol wire (Safak & Adams, 2002), electroactive polymers (Bar-Cohen, 2003), electroactive elastomers (electroelastomers; Pei et al., 2003), and ionic polymeric-conductor composites (IPCCs) (Shahinpoor, 2003). Kim & Shahinpoor (2007) have edited a recent review volume of papers on artificial muscle that readers should consult for further information. To date, the performances of these artificial muscles still do not approach that of the biological model, but new and innovative approaches along with refinements of current approaches will undoubtedly yield actuators with more strength, speed, and versatility than the devices presently available.

An element of performance that has too often been neglected is what has been termed fault tolerance. Animals in nature must be able to deal with injuries of one sort or another. Insects, for example, may lose one or more legs as they attempt to escape from a predator. A truly biomimetic robot ought to be able to continue to perform in spite of such drastic injury. Fault tolerance was considered theoretically by Ferrell (1995) and implemented in a distributed controller on a robot by Chiel et al. (1992). The topic has received more attention in recent years, with studies of faults ranging from simple joint malfunction to loss of one or more legs. For example, Yang has developed theoretical algorithms that will allow both quadraped robots (Yang, 2006) and hexapod robots (Yang, 2005) to continue to walk effectively even after a joint in one leg freezes. Inagaki (1999) and Chu & Pang (2002) have conducted a similar analysis, as has Parker (2005), who has also tested his control algorithm on a physical robot.

5. Bioinspired Robots as Test-beds for Investigating Biological Questions

5.1 The effects of biomechanical structure

Although there has been some discussion in the biological literature of the benefits that studying a robot may have for advancing understanding of biological processes (Beer et al., 1998; Ritzmann et al., 2000; Webb, 2001a), only a few robotics studies that have had an impact on the biology of locomotion have actually been conducted. The most prominent of these is study of the biomechanics of locomotion.

Until the work of Chiel & Beer (1997) and of Full and colleagues (e.g., Full & Tu, 1990), too little attention had been paid to the role of mechanics and the physical structure of an animal's body in its locomotor performance. The work of Full and his colleagues on walking in cockroaches (Full & Tu, 1991) and its expansion to a more general consideration of insect (Full et al., 1991) and then any legged walking (Full & Kodischek, 1999) made it clear that the structure of an insect's body played a major role in allowing it to walk rapidly and with agility. What was not clear simply from studying the biology was the contribution that specific morphological features played in this. Research on biomimetic robots helped answer this question by allowing researchers to assess the walking performance of robots that incorporated specific structural features from the animal model into the robot. By using such an approach, Quinn & Ritzmann (1998) were able to show that for cockroaches, at least, the distinct structures of the front, middle, and rear pairs of legs as well as the ability of the insect to flex its body during climbing, were important in allowing it to walk rapidly over irregular terrain. Recent progress and prospects for the future of this field have been reviewed by Koditschek et al. (2004).

Nearly all biomechanical work on walking and walking robots has been done using hexapods as models. However, some work has also been done on humanoid robots, where the problems of balance are severe. Witte et al. (2004) articulate several "principles" of humanoid walking that they arrived at from an analysis of biped walking in bipedal robots. These include, 1) human walking depends on elasticity as much as neuromuscular control, and hence rigid biomechanics cannot describe human walking sufficiently; 2) the trunk is an important component in walking; and 3) the ability of humans to twist the spine around the waist must be taken into consideration in an analysis of human walking. From an energetics point of view, Sellers et al. (2003) have used simulations of bipedal walking robots to test hypotheses about the evolution of bipedalism in early hominids, a project that would have been impossible without the robotics component.

5.2 The evolution of control architecture

The other research arena in which robotics has been used to study biological problems is in the area of locomotor control. Webb (2000, 2001a, b) lays out and discusses the central issues in the context of the study of animal behavior generally. In particular, she correctly points out that in spite of criticisms of the approach on the grounds that no mechanical construct can begin to approach the complexity of any biological model organism being studied for its walking, a serious attempt to build a robotic version of a walking animal has two potential benefits. First, in forces researchers to deal with every aspect of the problem under consideration. For example, until it was pointed out by Chiel & Beer (1997) that the physical structure of a walking animal was an integral component of the neurobiological control system by which walking is coordinated, neurobiologists had completely ignored the role that the biomechanics of the body might play in locomotion control. Hence, issues such as the role of compliance or the specifics of leg structure were not considered when hypotheses about the neural control of walking were posed. However, building a robot without compliant legs and actuators or with improperly structured legs quickly forces researchers to reassess these matters because the robot will not perform well. Second, it can, as Webb (2000) puts it, provide "insight into the true nature of the problem" by forcing researchers to come to grips with a problem if a robot that they believe ought to operate well does not do so. It is one thing to realize that a rigidly designed robot does not perform well, but it is quite another to recognize that lack of compliance may be the underlying problem.

Using salamanders as model organisms, Ijspeert and his colleagues have applied robotics to the biological problem of the evolution of vertebrate walking,. Salamanders swim like fish by undulating the body laterally when in water, but walk using a typical tetrapod gait when they are on land. Ijspeert et al. (2005) developed a multi-segmented, legged robot to study this multimodal behavior and developed a controller for both modes of locomotion based on chained, coupled oscillators (CPGs). They placed one set of CPG controllers in each of the body segments to control body movements during swimming, and four separate controllers in the body segments that contained the legs to control them. Simulation studies and implementation of the controllers in the robot suggested that a simple differential response to stronger activating signals to the CPGs would cause a transition from the slower walking to the faster swimming movements (Ijspeert et al., 2007). Study of the circumstances of transition from one mode of locomotion to the other in the simulated controller and in the robot led the researchers to the prediction that certain lesions in the central nervous system will knock out walking without impeding swimming. These predictions would not have been developed without the robotic and simulation studies; they can now be tested in animal experiments and may lead to new insights into the organization of the vertebrate pattern generator for locomotion.

6. Control of Locomotion – the Common Ground Between Biology and Engineering

6.1 Building a robot and testing controllers

Whether a researcher is a biologist interested in using robotic platforms to test hypotheses about animal movement or an engineer interested in incorporating biological principles into a robot, it is clear that a collaborative research effort will be required. At the early stages of such a collaborative effort, it will be helpful for biologists and engineers to have some common ground for discussion. The topic of how locomotion is controlled can serve as such common ground.

Any device that walks on legs, be it organic or mechanical, faces the same problems of coordination and balance (Delcomyn, 2004; Quinn & Ritzmann, 1998). The challenge for a biologist trying to understand the walking of an animal is identical to the problem of an engineer trying to design a control scheme for a walking robot that will allow the robot to move with agility over surfaces – in both cases, researchers must be able to explain how an adaptive pattern of leg movements is generated. Hence, this fundamental issue can serve as a focal point of discussions among members of the collaborative team.

A considerable amount of work has been done on controllers for walking as well as on the biology of locomotion control. From biological studies, we know that locomotion control in insects is modular (distributed) and hierarchical (Delcomyn, 1999). This means that higher neural centers (the brain) control the overall execution of the locomotion (speed, direction) and that local centers associated with each leg control the individual movements of that leg. Feedback from sensory structures in the legs interact with the local centers to help adapt movements to conditions. Vertebrates have a similar organization in spite of the significant differences in neural structure (Grillner, 1985; Grillner & Wallen, 2002). The local networks of neurons that control the movements of individual legs are known as central pattern generators (Delcomyn, 1999).

Many of the controllers developed for robots have been patterned on this organization. This includes controllers for insects (Arena et al., 2004; Beer et al., 1992; Dean et al., 1999), other arthropods (Ayers & Witting, 2007), and vertebrates (Fukuota et al., 2003; Ijspeert et al., 2005). Ferrell evaluated several different designs of controllers (Ferrell, 1995). The popularity of the approach is a reflection of its success in being able to control the complexity of legged locomotion.

6.2 Study of controllers in a simulation environment

The ultimate objective of developing a controller is, of course, to have that controller direct the walking of a physical robot. In many studies, however, controllers are developed and evaluated in simulation. It is obviously much easier to test a control structure in a simulation environment than it is simply to put it into a robot and hope that it does not fail and cause damage to the machine. The work of the Cruse laboratory (Kindermann, 2001; Schmitz et al., 2001) is a good example of this approach, though certainly others have used it as well (e.g., Klaassen et al., 2002).

An important innovation in the development of controllers in simulation is what is called the evolutionary approach (also called the genetic algorithm [GA] approach) for generating a useful controller. In very general terms, the method involves setting up a simulation in which the program is allowed to modify itself based on the degree to which a particular simulation run improves on the performance achieved by a previous run, according to a set of criteria set by the programmers. Hence, to evolve a control algorithm for a particular movement, researchers will set up a neural net with arbitrary connections between the inputs and outputs of the program and allow the program to run. As the simulation progresses, the connections are adjusted by the program itself as it evaluates its success in achieving its goal. In the end, the program will likely have generated a set of connections that will achieve the desired result given some appropriate input. See Kodjabachian & Meyer (1995) for an overview.

The method has been used in several specific applications. In some research, it has been used mainly to optimize the connections between independent CPGs (Kamimura et al., 2005). In other work, it has been used to evolve appropriate gaits (Mazzapioda & Nolfi, 2006; Parker, 2005). Since controlling six legs with multiple degrees of freedom can be a challenge, some researchers have also applied fuzzy logic to the problem (e.g., Pratihar et al., 2002), meaning that rather than striving for precise solutions, the algorithm is allowed to develop approximations. Still other researchers have used the genetic algorithm approach to evolve controllers that can handle obstacle avoidance (e.g., Filliat et al., 1999; Kodjabachian & Meyer, 1998). In the end, whether researchers reach this point or not, the objective is to place the evolved controller into a physical robot and allow it to control the robot. This transfer has been done successfully in some cases (e.g., Gallagher et al., 1996).

7. Conclusions

7.1 Where we are

It should be apparent from this review of biologically inspired robotics, as incomplete as it is, that the field is active, vibrant, and growing. Even robotics research on problems such as pathfinding and navigation in an open environment (Latombe, 1999; Pratihar et al., 2002; Go et al., 2006), which have usually seen a traditional engineering approach, have in recent years begun to incorporate biomimetic approaches and concepts into the field (Franz & Mallot, 2000; Meyer et al., 2005). There is also no question that engineers wishing to improve speed or agility of their walking robots now make at least some effort to incorporate biological concepts into their designs, as detailed in previous sections. It is only to be expected that future developments will incorporate even more biological principles and that future walking robots will begin to resemble their animal models more and more closely in their levels of performance.

The purported advantages of building mimics of biological systems in hardware and software have been articulated by several researchers in recent years, especially by members of the groups represented by Dean et al. (1999) and Quinn et al. (2003). It is no accident that these proponents of the approach are those who have most thoroughly integrated biologists and engineers into a viable working group.

Although proof of the value of the biomimetic approach is in the successful design of walking robots with superior performance, it is worthwhile to summarize here the general areas of the robotics of walking robots to which biological principles have made the greatest contribution – actuators, dynamics, sensory feedback, and locomotor control.

It has been obvious over the last decade or so that traditional actuators cannot begin to provide the speed and force relative to weight and power consumption that animal muscle can. Hence one significant contribution to robotics of biomimetic work is the stimulation of research into various non-conventional ways to move parts of the body (Kim & Shahinpoor, 2007). Work is already in progress on a variety of novel actuators, such as electroelastomers (Pei et al., 2003) and ionic polymeric-conductor composites (Shahinpoor, 2003) and it seems likely that even more will be developed in the near future.

A second contribution of biologically inspired robotics is the articulation of the concept that dynamic mechanics plays a significant role in animals in allowing them to run with speed and agility. Incorporation of biomechanical principles into robots has certainly contributed to the better performance of these robots (Altendorfer et al., 2001).

A third area of contribution is the recognition that sensory feedback is critical to a fully functional, agile walking robot (Schmitz, et al., 2001). This is perhaps the area in which robotics has lagged the farthest from incorporation of biological principles, in part because it is difficult to make artificial sensors that are effective yet small and light enough to be used in robots. This too, is an area of research that is active and likely to produce significant findings in the near term.

And finally, many engineers are incorporating the overriding principle of animal locomotion into their robots – that locomotor control is distributed. In most early robots, control was thought to require a centrally located system that took care of everything, from planning a gait to dealing with unexpected perturbances. However, it has been clearly established that all animals use a system of distributed and hierarchical control in which individual legs, even individual segments of legs, each have their own controller that is responsible for generating a basic back and forth movement (see Delcomyn, 1999 for discussion of this organization in insects). These controllers interact with one another and with sensory feedback to generate a suitable gait on the fly, with no central control being responsible for every detail of foot placement and gait generation. Higher centers are responsible for overseeing matters such as the speed and direction of locomotion. There is no question that robots incorporating this principle perform better over rugged terrain than would conventionally controlled robots.

7.2 Where we can be

What can be done to advance the field? First, and obviously, additional research will help, not just in the application of biological knowledge to engineering problems, but on the biological systems themselves. It is all very well to say that incorporating more biological knowledge into the design of a walking robot will improve the performance of that robot, but the fact of the matter is that biologists still do not have a complete understanding of how walking in any animal is generated, controlled, and regulated. Hence, biorobotics will benefit from additional biological research as well as engineering work.

Second, and perhaps not so obviously, the field would benefit greatly from development of a set of standard tests that can be used to evaluate the performance of individual robots. Perhaps the single most striking difference between biological and engineering work is that the latter often has as its outcome a physical object. As noted by Delcomyn (2004), this object is often described in the literature mainly as a proof of concept. If the objective of biorobotics is to improve the performance of robots in the real world, then it is essential that robots be subjected to real tests of performance. Clearly, the kind of tests to which a robot might be subjected will vary from robot to robot and be different for robots that have different performance objectives. It is also clear that researchers will tend to use tests that show the particular virtues of their own creations. Nevertheless, certain performance results, such as speed of progression, minimum turning radius, ability to back up, ability to right itself, or ability to travel over obstacles, can reasonably be expected for any walking robot. As results begin to appear in the literature, they will serve as a powerful impetus to researchers to improve the performances of their robots.

It is gratifying (and in many ways a reflection of the maturation of the field) that there is indeed an increasing attention to performance. Saranli et al (2001) gives the specifications and speeds of several biomimetic robots, hence providing a useful comparison of the status of robot performance at the beginning of the 21st century. Clark & Cutkosky (2006) give performance information about the recent Sprawl robot. Moore & Buehler (2001) and Weingarten et al. (2004) give some performance features of the RHex robot. It would be helpful, however, if performance over some standard course or test were to become a required component of any publication that describes a fully functional robot. If nothing else, it will allow researchers who have designed the top performers to demonstrate to those who have provided research support that the funds have been well spent.

A third suggestion (Delcomyn, 2004) is to take a page from biological science and apply the experimental method and hypothesis testing more explicitly to robotics projects. Certainly, any successful robot that is built is inevitably the result of a long, informal process of trial and error, which in a sense can be seen as a series of tests of various hypotheses as to what will work for a specific purpose. However, this can be made much more explicit by articulating specific and testable hypotheses about the efficacy of some particular control method or physical structure. Certainly it can be time consuming and expensive to implement various competing ideas about how a robot ought to be constructed, but thinking in terms of explicit hypothesis testing can sharply focus the mind on elements that are really important, and hence speed progress in the long run.

Biologically inspired robotics has emerged in the last decade as a strong and vibrant field of research. There is little doubt that this fusion of biological insights with more traditional engineering approaches will continue to have an invigorating effect on robotics research. In another decade, it seems likely that researchers will hardly recognize the field.

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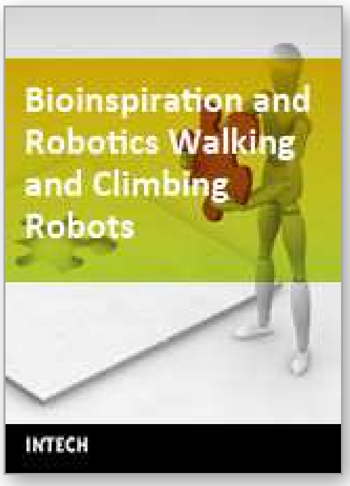

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Nature has always been a source of inspiration and ideas for the robotics community. New solutions and technologies are required and hence this book is coming out to address and deal with the main challenges facing walking and climbing robots, and contributes with innovative solutions, designs, technologies and techniques. This book reports on the state of the art research and development findings and results. The content of the book has been structured into 5 technical research sections with total of 30 chapters written by well recognized researchers worldwide.

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