Bio-inspired climbing robots

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14.1 Introduction

Climbing robots are a special breed of service robots developed in the last three decades and used for many tasks including inspection, cleaning, and maintenance of tall structures, which involve safety risks to human operators. Until now, more than 200 prototypes of climbing robots have been reported (Chen et al., 2006), with a wide range of sizes and weights and employing many different technologies. While there are several ways to climb a wall using various methods not previously observed in nature like, for example, wheels for the mobility and magnetic force for the adhesion to the surface, in nature, climbing is performed by crawling, snaking, and more often in more complex intelligent natural systems, with a combination of legs and grippers (Tavakoli et al., 2010a).

In this chapter, we explore the novel bio-inspired mechanisms used in climbing robots for adhesion and locomotion.

Bio-inspired robotics is about learning from nature and highly complex and efficient biological systems, and developing similar mechanisms that may solve a specific problem in the engineering field. The designer should then try to simplify and enhance that mechanism for the particular task of interest. The developed robotic system may outperform its corresponding biological inspiration, for this specific task.

When designing climbing mechanisms, there are basically two sets of problems and questions that should be answered in the early stages of the design. In the conceptual design stage of a climbing mechanism for a specific purpose, one needs to address:

A. What kind of adhesion mechanism should be applied to hold the mechanism on the vertical surface?

B. What type of locomotion mechanism should be utilized for climbing the specific type of structure?

These two problems are closely interrelated. One cannot be answered without taking into consideration the other. The former problem, the adhesion mechanism is a critical part of the climbing mechanism and should be specifically designed and optimized for a particular case. A lightweight and simple adhesion mechanism results in an overall lighter robot; thus, less power consumption and more autonomy for the robot can be granted. Regarding the adhesion mechanism of a climbing robot, one of the aspects that a designer needs to evaluate is the existence of any specific feature in the vertical surfaces that the robot should climb, that the adhesion mechanism may rely on. Taking advantage of these specific features of the environment is very important for design of lightweight robots with high maneuverability. For instance, if the climbing surface is

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ferromagnetic, many times a magnetic adhesion unit is the best choice, since it provides a very high adhesion force to weight ratio. Relying on specific features of the surface can be seen also in climbing animals. For instance, squirrels rely on the surface irregularities to hang their claws. But some animals such as snails can climb from a wider range of surfaces, as they take advantage of chemical adhesion.

The locomotion mechanism of the climbing robots depends significantly on the adhesion unit. Adhesion units should support the weight and the resulting torque of the whole robot in static and dynamic modes. Higher adhesion force to weight ratio in the adhesion units leaves a bigger space for increasing the overall robot performance in terms of autonomy, maneuverability (i.e., adding more active degrees of freedom (DoF)), and lifting weight. In this chapter, we intend to give an overview of the bio-inspiration in climbing animals in terms of adhesion and locomotion.

The first section is dedicated to bio-inspired adhesion technologies, ranging from mechanical fit used by most large climbing animals to wet and dry adhesion techniques used by small insects and reptiles. We also study microsynthetic adhesives which mimic gecko hair, chemical adhesion of the snails, or adhesion by suction, used by limpets. Other particular concepts such as posture change and pruning robots are also addressed.

The second section addresses the biomechanics involved in the locomotion of the climbing robots. This section comprises recent developments on legged robots, snake robots, spider robots, pendulum robots, brachiating, and others. In this section, we also briefly explore the bio-inspired mechanisms such as tails, dynamic balancing platforms, gliding membranes, etc., that are used to improve the robot's locomotion and balance and to allow obstacle surpassing and planar transitions.

The final section discusses the current challenges and limitations that robot designers face and likely future trends in this field. Some useful sources for further information and most prominent research and interest groups to follow on this robotics research field are presented.

14.2 Bio-inspired adhesion technologies

Climbing robots can be classified according to the mechanisms they employ for adherence and locomotion. The correct choice and use of these mechanisms is the main challenge when developing a climbing robot. In this section, we discuss the main bio-inspired adhesion technologies employed in this field.

Adhesion principles can be mainly distinguished based on two criteria (Longo and Muscato, 2008):

- Physical principle generating the adhesion force (e.g., mechanical fit, suction, etc.);
- Energy needed for generating the adhesion force (passive or active).

14.2.1 Mechanical seizing

Some climbing robots' adhesion technologies draw inspiration from arboreal organisms. These animals display many specializations for dealing with the mechanical challenges of moving through their habitats. For instance, primates use frictional gripping relying upon hairless fingertips. This type of mechanical adhesion allows them to hold to tree branches by squeezing the branch between the fingertips, thus generating frictional force. However, this type of grip depends upon the angle of the frictional force. Larger branches result in reduced gripping ability. Animals other than primates that use mechanical gripping, or seizing, in climbing include the chameleon, which has mitten-like grasping feet, and many birds that grip branches in perching or moving about. 3D Climber (Tavakoli et al., 2010b; Tavakoli et al., 2005) is an example of a developed robot that is inspired by mechanical seizing and use a four DoF arm and seizing grippers to move through complex three-dimensional environments possessing several bends and branches, in a similar way to what primates do (Figure 14.1).

Another type of robots possesses special grippers designed to adapt to specific features on their environment, such as the vertical moving fire fighting robot (Amano et al., 2001), which is capable of gripping handrails and quickly climb balconies on high-rise condominiums.

14.2.2 Mechanical form fit/penetration

Another type of mechanical adhesion that relies on penetration on smooth surfaces is achieved by animals which possess sharp claws or similar mechanisms. They also allow reorientation of the direction of forces the animal applies. Squirrels are a good example of animals which use their claws to grab to and climb tree trunks, having evolved highly mobile ankle joints which permit rotating the foot into a "reversed" posture. This allows the claws to hook into the rough surface of the bark, opposing the force of gravity.

Figure 14.1 3D Climber robot (on the left), developed at the University of Coimbra, is a step-by-step climbing robot which draws inspiration from the climbing and gripping techniques of primates, shown on the right image.
(Image courtesy of Hagit Berkovich.)

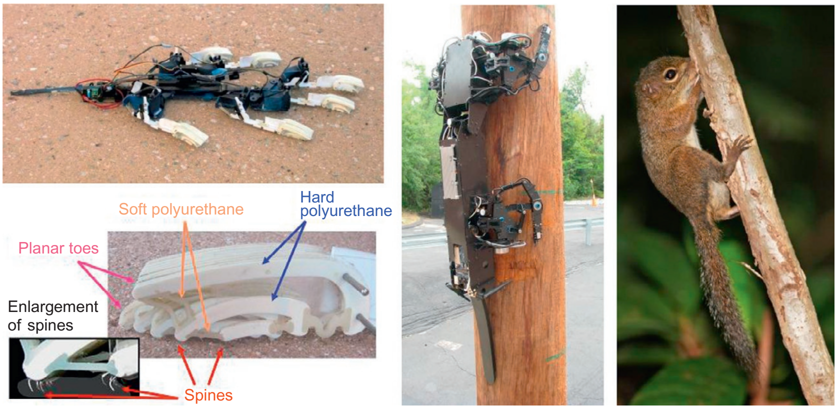

Figure 14.2 SpinyBot (on the left) developed at Stanford uses a novel patented technology that enables it to climb smooth, rough, uneven, porous, and dirty surfaces using arrays of small spines, which hook onto bumps and pits on the surface. In the center is the RiSE V3, another example of the use of micro spines for gripping the surface, just like squirrels, on the right, do with their claws.
(Image courtesy of Ben Twist.)

Spinybot from Stanford University (Kim et al., 2005; Asbeck et al., 2006) is a small climbing robot which uses several micro spines in its feet, which work just like claws, allowing it to adhere to the climbing surface. Another example of use of micro spines to penetrate the climbing surface is the RiSE V3 (Haynes et al., 2009), pole climbing robot. With a mass of 5.4 kg and employing several bio-inspired technologies, including flexible joints, complex leg motion, and balancing tail, this quadrupedal robot is capable of climbing wooden telephone poles with speeds up to 21 cm/s (Figure 14.2).

14.2.3 Wet adhesion and suction

Most of the small animals possess more complex adhesion mechanisms, including wet and dry adhesion, relying on van der Waals forces, fluid-mediated adhesive forces, and pneumatic and suction forces (Figure 14.3).

Wet adhesion, common in flies and beetles, functions either by suction or by capillary adhesion. Limpets use a combination of shell clamping, glue-like adhesion, and suction as adhesion mechanisms. Suction is mainly used when they need mobility, relying on stronger glue bonds (mean tenacity of glue-like adhesion is approximately equal to 0.23 MN/sq m and the mean tenacity of suction adhesion is approximately equal to 0.09 MN/sq m) and shell clamping rather than continuous muscular effort for long-term attachment (Smith, 1992; Smith, 1991; Ellem et al., 2002).

WallWalker (Miyake et al., 2007), developed at the Kagawa University in Japan, is an example of a climbing robot developed for window cleaning which uses wet adhesion and suction (Figure 14.4). Other robots which use suction for adhesion include the Roma (Balaguer et al., 2002; Balaguer et al., 1998), vortex-based suction robot (Bonaccorso et al., 2008), climbing robot with multiple suction chambers (Hillenbrand et al., 2008), among others.

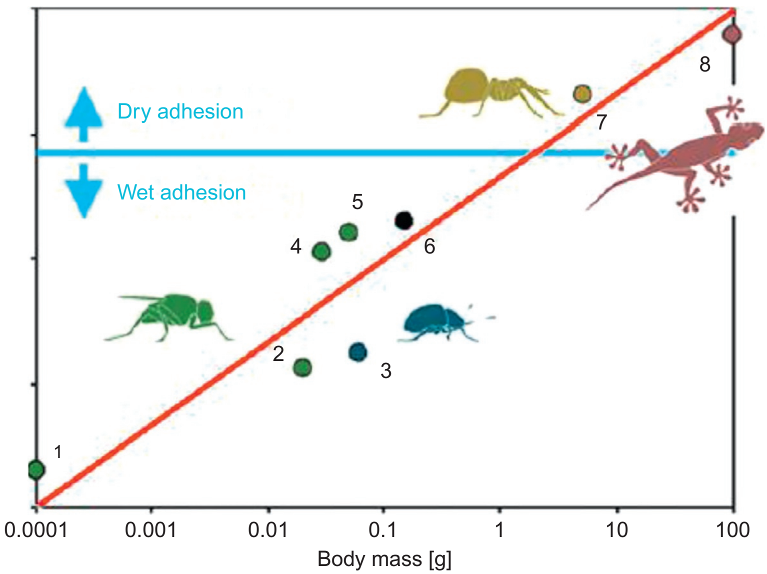

Figure 14.3 Adhesion mechanism according to body mass, for small animals. 1, 2, 4, 5: flies; 3: beetle; 6: bug; 7: spider; 8: geckonid lizards. Adapted from the book "Attachment Devices of Insect Cuticle" by Gorb (2001) and taken from Gorb et al. (2007) © IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved. The systems located above the blue line rely on van der Waals forces (dry adhesion), whereas the systems below the line rely mostly on capillary and viscous forces (wet adhesion).

Figure 14.4 On the left, the WallWalker window cleaning climbing robot. On the right, an example of natural wet adhesion with suction used by limpets
(photo courtesy of Jay from Naturebum).

Contrary to one may think, the Madagascar's endemic sucker-footed bat (*Myzopoda aurita*) does not rely on suction for adhesion. In fact, it clings head-up to smooth leaves using specialized pads on its wrists and ankles (Riskin and Racey, 2010). This form of wet adhesion allows them to unpeel easily from the surface because of deformation of the pads, during crawling, but would also cause passive detachment if bats roosted

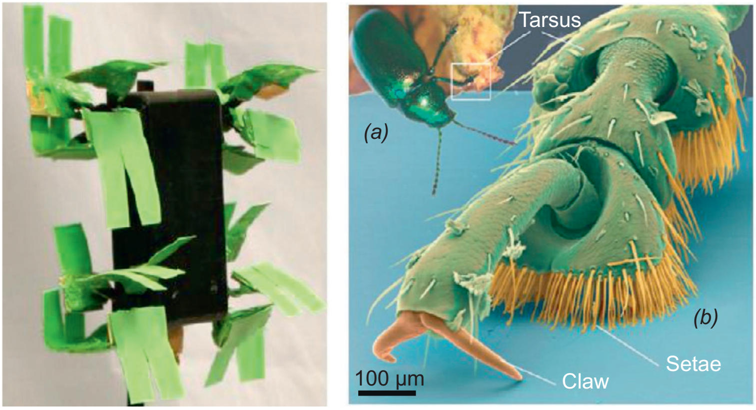

Figure 14.5 On the left, the Mini-Whegs™ wet adhesive pad climbing robot and on the right an example of the hairy attachment system (taken from Gorb et al. (2007) © IOP Publishing. Reproduced by permission of IOP Publishing. All rights reserved). Tarsus (b) of the chrysomelid beetle *Gastrophysa viridula* (a) attached to the smooth surface Gorb (2005) (colored scanning electron microscopy picture is the courtesy of Juergen Berger, MPI for Developmental Biology, Tubingen, Germany) and taken from Gorb et al. (2007) © IOP Publishing.
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head-down, like the vast majority of bats do, hanging by their toenails (Riskin et al., 2009). This provides an ecomorphological explanation to the head-up roosting behavior of these unique bats.

Mini-Whegs™ (Gorb et al., 2007) is a small climbing robot which uses wet adhesion through a patterned tape on four whegs (Figure 14.5).

14.2.4 Dry adhesion

Dry adhesion is best typified by the specialized toes of geckos. The gecko's trick to sticking to surfaces lies in the very fine hairs on its toes. Literally, billions of these tiny hairs make contact with the surface and create a huge collective surface area of contact. Each hair is made from multiple sections, a micro-hair which is roughly 5 µ in diameter, and atop each of these micro-hairs sit tens to hundreds of nano-hairs which are 200 nm in diameter (1/250th of a human hair) in a tree-like branching structure (Murphy and Sitti, 2009). This, in conjunction with van der Waals forces allows them to adhere to many substrates, even glass. Geckobot (Unver et al., 2006), StickyBot (Santos et al., 2008), and Waalbot (Murphy and Sitti, 2009) are gecko-inspired climbing robots which use elastomer adhesives on their fingers to adhere to the climbing surface (Figure 14.6). The Geckobot is a 100 g climbing robot with a body made of Delrin and adhesive polydimethylsiloxane elastomer surfaces on its four feet. To pull the adhesive surfaces from the surface during locomotion, it employs a peeling mechanism actuated by the leg motor and a compression spring. This allows for

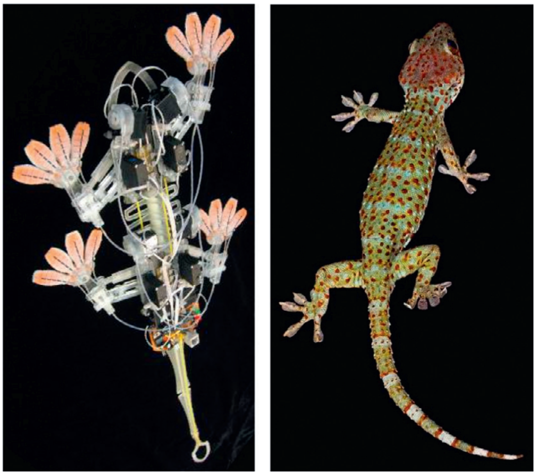

Figure 14.6 On the left is the StickyBot and on the right is an underside view of a Gecko showing the details of its fingers.

power-efficient detachment as seen in geckos. Its total length is 190 mm and width is 110 mm. It is capable of climbing with speeds up to 1 cm/s on inclined surfaces up to 85° (Unver et al., 2006). However, this is not an adhesion technology limitation. The StickyBot employs a synthetic adhesive patch termed directional polymer stalks on each of the four toes of each of the four feet. The limit surfaces, representing the friction and adhesion limits associated with a synthetic directional adhesive material, for individual patches are combined and linearized to produce a set of contact constraints for each foot of a climbing robot. The limit surfaces are convex and they intersect the origin in force space. These properties lead to efficient strategies for controlling internal forces between the feet to maximize the margin of stability with respect to disturbances and for attaching and detaching the feet smoothly, without unproductive energy expenditure. This feature allows the StickyBot to cling to surfaces with an overhang angle of at least 20° (Santos et al., 2008). Because the limit surfaces are asymmetric, foot orientation is also important. Observations of geckos reveal that they change the orientations of their feet, for example, when clinging to a ceiling or when running headfirst down a wall (Santos et al., 2008). This, however, is not yet used in any of these small gecko robots.

14.2.5 Chemical adhesion

Snails segregate a fluid which acts as glue to provide the necessary adhesion to the surface. The snail inspired wall climbing robot (Shapiro et al., 2005) works in a similar way by carrying hot-melt adhesive tubes which are heated and released as liquid into the robot tracks, as the robot moves, acting as a glue for the robot (Figure 14.7). Other similar robots using hot melt adhesives have been proposed by the Bio-Inspired Robotics Lab (BIRL) of ETH Zurich (Osswald and Iida, 2011; Wang et al., 2012; Wang et al., 2013). These robots combine high-payload capabilities with the ability to climb on various vertical terrains.

Figure 14.7 The snail-inspired wall climbing robot uses the same adhesion mechanism as a snail, by releasing a visa glue fluid which acts as glue.
(Snail photo by John D.)

However, similar to snails, these robots have the disadvantage of low climbing speeds, rating at 0.039 cm/s climbing speed, in the case of the small climbing turtle (Graber, 2012). This is mainly due to the time that they require to melt and solidify the glue. They are also extremely inefficient in terms of energy (Graber, 2012).

For arboreal animals, posture and balance are extremely important when climbing, due to the height of many branches and the potentially disastrous consequences of a fall. On horizontal and gently sloped branches, the primary problem is tipping to the side due to the narrow base of support. The narrower the branch, the greater the difficulty in balancing a given animal face. On steep and vertical branches, tipping becomes less of an issue, and pitching backward or slipping downward becomes the most likely failure (Cartmill, 1985). The same applies to climbing robots. However, most arboreal animals possess clever features which allow them to overcome such difficulties. Many arboreal species lower their center of mass to reduce pitching and toppling movement when climbing. This may be accomplished by postural changes, altered body proportions, or smaller size (Cartmill, 1985). The pruning robot developed by Kawasaki et al. (2008) and Ishigure and Kawasaki (2013) can stay on a tree without energy consumption by using its own weight using a two-DoF posture adjustment mechanism to keep the pruning robot in a horizontal posture (Figure 14.8).

Figure 14.8 On the left, the pruning robot adjusts its posture to stay on the tree using only its weight. The same technique is used for centuries by coconut tree climbers.

14.3 Bio-inspired locomotion mechanisms

Climbing animals can be roughly divided into two groups: those animals which move steep, vertical, or overhanging surfaces (surface locomotion), and those who move among tall vegetation (arboreal locomotion). These two environments may produce quite different climbing methods. Anatomical specializations of arboreal locomotion animals include (Tavakoli et al., 2010a):

- Elongated limbs that assist them in crossing gaps, reaching fruit or other resources, testing the firmness of support ahead, and in some cases, brachiating.
- Prehensile tails, such as chameleons, spider monkeys, and possums, in order to grasp branches.

14.3.1 Brachiation

One of the most efficient locomotion mechanisms used by arboreal climbing animals is called Brachiation. This specialized form of locomotion is used by some primates (spider monkeys and gibbons, occasionally female orangutans) to move very rapidly while hanging beneath branches. It involves swinging with the arms from one handhold to another. Prehensile tails play a major role in this form of locomotion by acting as a gripper and by helping with balance. Gibbons are the experts of this mode of locomotion, swinging from branch to branch with distances up to 15 m, and traveling at speeds of as much as 56 km/h (Tavakoli et al., 2010a). While some pole climbing robots using grippers, such as the 3D Climber (Figure 14.1), may appear to follow this principle, they cannot be fully considered as brachiating robots since their locomotion is step by step and does not possess the dynamics of the brachiation.

A couple of works have been conducted on brachiating robots. Fukuda et al. (1991) proposed and simulated a brachiating robot design. Saito and Fukuda (1996) extended this work to create a three-dimensional robot closely resembling a siamang, called Brachiator-III. The robot consists of 12 DoF controlled by 14 motors, 2 of which are responsible for grasping. This robot is able to initiate brachiation from a stationary hanging position and continue moving beneath a horizontal series of ladder-like rungs. Kajima et al. (2003) constructed an even more complex robot consisting of 19 links and 20 actuators, called "Gorilla Robot II." It was designed to be able to walk bipedally or quadrupedally and brachiate, depending on the requirements set by the environment or task. It has the approximate proportions of a siamang and weights 20 kg (Bertram, 2004).

According to the studies (Usherwood et al., 2003; Usherwood and Bertram, 2003), the reason that the gibbons who weigh usually less than 10 kg, can brachiate on 56 km/h is that they do not generate torques on their shoulders and even the amount of torque on their handhold is surprisingly less than 2 N m (Chang et al., 2000). Gibbons use potential to kinetic energy conversions and vice versa for accelerating and decelerating. This method might be studied in order to reduce the amount of the necessary torque on joints, thus reducing the size of the motor and consequently reducing the total weight of the system. While passive walking has been extensively studied and applied, and there are also many interesting works on passive grasping, only until some years ago, researchers have started to study and model the interplay of passive locomotion, climbing, grasping, and body inertia management. Toshio Fukuda, director of the Micro-Nano Control and Bio-Robotics Laboratory at the Nagoya University in Japan, has been particularly active in this research topic (Kajima et al., 2004; Fukuda et al., 2006; Pchelkin et al., 2011).

14.3.2 Dragline locomotion

Recently, a novel bio-inspired locomotion mechanism has been developed by researchers from the Bio-inspired Robotics Lab at ETH of Zurich. Inspired by spiders producing draglines to assist locomotion, the dragline-forming mobile robot utilizes an alternative mobile technology where it achieves locomotion from a solid surface into a free space. The technology resembles the dragline production pathway in spiders to a technically feasible degree and enables robots to move with thermoplastic spinning of draglines (Figure 14.9). Thermoplastic adhesives are used as source material for the draglines. Experimental results show that a dragline diameter range of 1.17–5.27 mm was achievable by the 185 g mobile robot in descending locomotion from the solid surface of a hanging structure with a power consumption of 4.8 W and an average speed of 5.13 cm min^{-1} (Wang et al., 2014).

14.3.3 Limbless locomotion

Other different locomotion concepts observed in nature come from limbless animals, such as snakes or caterpillars. Many species of snakes are highly arboreal, and some have evolved specialized musculature for this habitat (Jayne, 1982). While moving in arboreal habitats, snakes move slowly along bare branches using a specialized form of

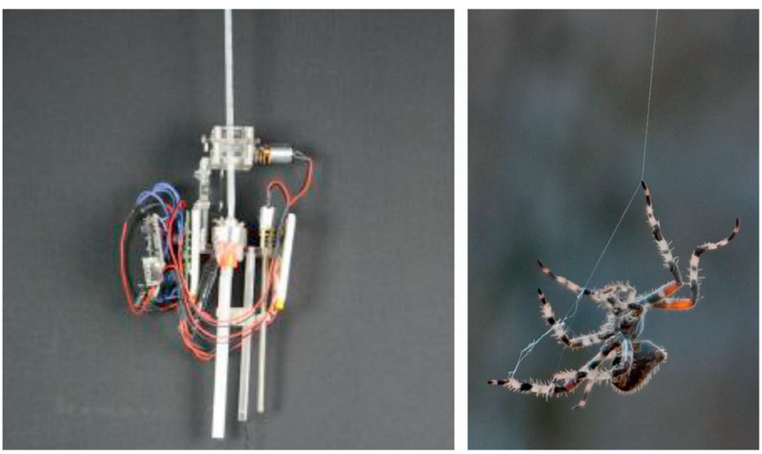

Figure 14.9 The ETH dragline-forming mobile robot, on the right, draws inspiration from spiders (spider photo credit: Stevie Benintende—www.whatsteviesees.com).

concertina locomotion (Astley and Jayne, 2007), but when secondary branches emerge from the branch being moved on, snakes use lateral undulation, a much faster mode. As a result, snakes perform best on small perches in cluttered environments, while limbed organisms seem to do best on large perches in uncluttered environments (Astley and Jayne, 2009).

Many robots which use this locomotion concept have been developed (Transeth et al., 2009; Yim et al., 2001; Wright et al., 2007a; Hopkins et al., 2009; Electric Power Research Institute, 2010). Their high number of DoFs and flexibility allows for easy obstacle surpassing and usability in any environment and surface type, making this concept of locomotion a specially promising one in the field of service climbing robots. Carnegie Mellon Biorobotics Lab researchers are especially active in developing several types of climbing and swimming inspection snake robots (Rollinson et al., 2013; McKenna et al., 2008; Wright et al., 2007b). Their 16 DoF, 2.9 kg climbing snake robot (Wright et al., 2012) is capable of climbing poles, trees, and branches just like snakes do (Figure 14.10).

Based on the vermicular motion of the pine caterpillar and inchworm, Wei Wang et al. proposed a two novel module climbing caterpillar robot with seven DoF (Wang et al., 2008). This small and lightweight climbing robot is capable of using two crawling principles of two typical caterpillars, pine caterpillar model and inchworm model, to climb vertical walls (Figure 14.11). The Softbot, developed at the Biomimetic

Figure 14.10 The CMU unified snake robot climbing a tree. This locomotion concept draws inspiration from snakes.

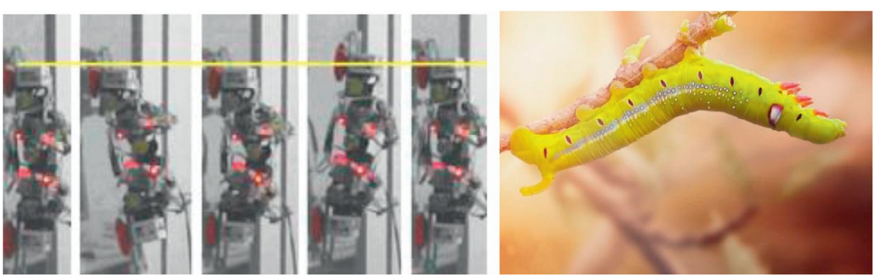

Figure 14.11 The caterpillar robot by Wei Wang et al., on the left, climbs walls using the crawling principles of caterpillars.

Devices Laboratory at Tufts University, is a soft robot which is continuously deformable and capable of collapsing and crumpling into small spaces. It is also based on the biomechanics and neural control system of a caterpillar (Trimmer et al., 2006).

14.3.4 Dynamic climbing

Other robots use climbing techniques inspired by climbing animals such as geckos and cockroaches, which rely on their own internal dynamic motions to gain height. The Dynamic Single Actuator Vertical Climbing Robot (Degani et al., 2007) benefits of its own internal dynamics that allows it to climb with only a single actuated DoF. By using a pendulum driven by an actuator, they manipulate the internal dynamics of the robot and the movement of its body, enabling it to move and climb while it rotates between two walls. Clark et al. also proposed a bio-inspired, two DoF vertical "running" robot assisted by springs. This robot also benefits from internal dynamic motions by employing the pendulous climbing model which shows remarkable similarities in dynamic wall-climbing behavior exhibited by many different animal species (Clark et al., 2007). Another small and lightweight climbing robot proposed by Dickson uses the Full-Goldman template for dynamic climbing and a single actuator to drive a miniature bipedal dynamic climbing platform, through the use of gears and springs (Figure 14.12; Dickson et al., 2013).

Other robots use tails, just like squirrels, primates, or reptiles, to manipulate their internal dynamic motions and enable them to climb. The ROCR: An Energy-Efficient Dynamic Wall-Climbing Robot (Provancher et al., 2011) is a pendular, two-link, serial chain robot that utilizes alternating handholds and an actuated tail to propel itself upward in a climbing style based on observation of human climbers and brachiating gibbons (Figure 14.13). Other already referenced climbing robots which use tails for balance include the Geckobot (Unver et al., 2006), StickyBot (Santos et al., 2008),

Figure 14.12 The miniature bipedal dynamic climbing platform, on the left, climbs walls with a single actuator taking advantage of its own internal dynamic motions, similar to the way animals and humans climb vertical walls.

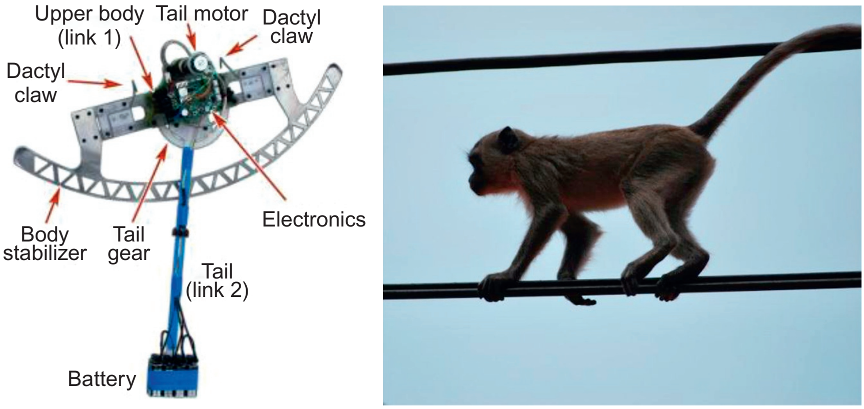

Figure 14.13 The ROCR robot on the right uses a tail to propel itself upward in a climbing style based on observation of brachiating gibbons.

and Waalbot (Murphy and Sitti, 2009). Some robots use their tails to climb steeper inclines without toppling, as is the case of the HELIOS Carrier (Guarnieri et al., 2009). Some climbing and jumping robots even use their tails for pitch control (Libby et al., 2012).

14.3.5 Multimodal locomotion

A type of locomotion which combines climbing and flying for a fast, agile, and efficient movement is the multimodal locomotion.

There are several examples of animals capable of multimodal locomotion. While climbing and gliding may not be necessarily more efficient than simply running (Byrnes et al., 2011), it is often used for overcoming obstacles, escaping predators, avoiding rough or complicated terrain, or simply quickly transit between tall vertical structures. A theory on the evolution of flight proposes a "top-down" approach (animals jumping from heights) with an intermediary gliding phase for arboreal climbing animals (Norberg, 1985).

The Draco genus of lizards, also referred to as "flying dragons," comprises more than 40 species of lizards, with body sizes ranging in mass between 3 and 20 g (McGuire and Dudley, 2011; McGuire and Dudley, 2005), which have developed the ability to glide and special physical adaptations to actively control their aerodynamic properties. Using elongated thoracic ribs and specialized musculature, they are able to actively control the aerodynamic properties of their gliding membrane, called patagium (McGuire and Dudley, 2011; Russell and Dijkstra, 2001). Draco lizards have also shown other physical adaptations along their necks, legs, and edges of their hind quarters that are used for maximizing the aerodynamic surface (McGuire and Dudley, 2011).

Other reptiles with radically different morphologies are also capable of gliding. Snakes in the genus Chrysopelea have shown the ability to glide using behavioral and physical adaptations to create an airfoil-shaped body to substantially decrease their descent accelerations. There are five species of "flying snakes" that flatten their bodies, increasing the surface area, and form a concave bottom surface creating an effective whole-body wing (Socha et al., 2010). The *Chrysopelea paradisi*, or the paradise tree snake, has even been shown to temporarily achieve a positive (upward) acceleration during flight (Socha et al., 2010).

But probably the most well-known examples of gliding animals are the flying squirrels. Like the above-mentioned reptiles, they also reveal special physical adaptations evidenced by the stretched patagial skin between their fore and aft limbs used for controlled gliding (Galvao et al., 2006). They have been observed to have glide ratios of up to approximately 3, e.g., a 30-m glide over a 10-m drop (Clark and Dickson, 2013). Some species of flying squirrel have shown the ability to modify the shape of their gliding membranes in flight using the abductor of the thumb. Due to this adaptation, small flying squirrels, in particular *Glaucomys Volans*, are extremely agile and maneuverable (Thorington et al., 1998). These animals have been reported to have glided durations of up to 15 s (Asari et al., 2007; Byrnes et al., 2008).

Researchers from Florida State University College of Engineering proposed the ICAROS platform which is capable of climbing prepared vertical surfaces and transitioning to a glide path with performance characteristics comparable to its biological counterparts (Clark and Dickson, 2013). Using the same iplatform, climbing platform proposed by Dickson et al. (2013), the ICAROS platform, with a mass of 350 g, is capable of climbing a carpet wall at 0.135 ± 0.01 m s^{-1}. When it reaches the top, it is able to glide thanks to its fixed-wing glider profile made of balsa wood, with a wing span of 72 cm, thus effectively combining these two forms of locomotion into a single platform. The ICAROS platform is capable of a glide ratio of approximately 2 m s^{-1} and a glide velocity of approximately 5.3 m s^{-1} on par with climbing and gliding animals. Same researchers are already working on the next generation of ARM2 S that utilizes a bio-inspired, flexible patagium for gliding flight similar to structures seen on flying squirrels and flying dragons. The platform will incorporate specialized, compliant feet for operation on numerous surfaces (Clark and Dickson, 2013).

14.4 Size and current technology constrains

While most small animals such as geckos and insects, as seen previously, rely on dry and wet adhesion, big animals such as gibbons and monkeys rely mostly on the dexterity of their body and use this dexterity to encircle and seize the object. They do not use specific adhesion techniques such as wet or dry adhesion. This is same for even heavier animals such as pandas and bears.

For climbing robots, if small robots are desired for applications such as video monitoring, bio-inspired adhesion, e.g., dry adhesion can contribute to the development of lightweight and fast robots. However, if the robot is required to carry bigger weights, such as inspection probes or cleaning and maintenance tools, the focus should be mainly on the locomotion mechanism. Arboreal animals take advantage of a complex and high dexterity locomotion mechanism with many DoFs. Due to the limitations in the current technologies, such as actuators (Tavakoli et al., 2010a), the bio-inspiration of the robot at this scale is still very limited. Reaching to the dexterity level of such animals is a challenging problem in terms of design, optimization, and implementation of the mechanical structure. It is also a challenging control problem. Researchers always tried to limit the number of DoFs of the climbing mechanism by scarifying the robot's maneuverability.

For example, a human arm alone has seven DoFs (not considering the fingers). According to Clauser et al. (1969), the average mass of the human arm is about 3.2 kg. Another analysis made with 44 male basketball players showed that the average value of their pick elbow torque on flexor is 103 N m and their shoulder joint is 160 N m. On the other hand, a single brushless motor equipped with a harmonic drive reduction (like the ones employed in the 3D Climber pole climbing robot (Tavakoli et al., 2010b)) can deliver about the same torque (160 N m) but weighs 4.2 kg. This simple example shows that with the current technology driving one DoF of an arm requires an actuator heavier than the total human arm. In another work, Tavakoli et al. analyzed the application of pneumatic muscles in robotic applications and climbing robots (Tavakoli et al., 2008) and concluded that application of pneumatic muscles would be even heavier than harmonic drive actuators.

After decades of investigation on humanoid robots by several research groups all over the world, now we can see humanoid robots that can walk, run, play football, dance, and climb the stairs. Yet humanoid robots cannot perform agile movements that are associated with impacts, such as jumping, because they cannot store kinetic energy.

The new developments of serially elastic actuators (SEAs) and, more recently, variable stiffness actuators (VSAs) are some important steps toward development of actuators that are tolerant to impact and are safe to be applied in robots that should interact with humans. New developments in soft and elastic robots are another recent and quickly growing area that can contribute in this field. Several types of soft robots are being developed in many research centers. In addition to being inherently safe, soft robots are generally more adaptive to their environment. Adapting to the environment is one of the key issues in the design and development of grasping and adhesion mechanisms for climbing robots. In summary, recent and continuing advances in new and lightweight actuators, SEAs and VSAs, soft robots such as soft articulated arms and adaptive grasping mechanisms, and finally in development of smart controllers that apply the biological control schemes, such as synergies, can contribute in the development of the next generation of bio-inspired climbing robots at a scale that can carry a reasonable payload for inspection, surveillance, and maintenance services.

14.5 Future trends

The continuous development of actuators with a higher power to weight ratio, the growth of 3D printing and manufacturing technologies, advances in the adhesion technologies, and soft and deformable robots will contribute in the development of future lightweight and agile miniature bio-inspired robots. At this scale, the effect of the robot mass and gravity will be less relevant, thus simplifying the robot mechanical structure, adhesion, and locomotion mechanisms, and reducing the amount of power needed to drive the robot. However, for bigger climbing robots that require carrying higher payloads, the problem is still to be addressed. At this scale, in addition to the adhesion problem, one of the biggest limitations for robotic designers comes from the actuator technology.

Scaling down on the size and complexity of drivers and actuators, in line with the development of more powerful processors and controllers, will allow researchers to explore complex locomotion concepts such as the snake motion, which possesses large potential in terms of climbing performance, adaptation to different environments and obstacles, speed, and maneuverability. Also, the theoretical study of the dynamical interplay of locomotion and gripping/grasping/clasping of under actuated legged climbing systems equipped with (rudimentary) hands has still to be performed. Moreover, the development of "frugal" control systems exploiting the robot "body" dynamics and managing the locomotion and grasping within a high-level holistic unified framework, as probably happens in nature, has yet to come.

Soft robotics (Lam and Xu, 2012) will also be an important future trend, exploring new areas of material sciences and mechanics to produce mechanisms capable of fully adapting to the environment and its surroundings, just like organisms do. With a soft structure and redundant DoFs, these robots can be used for delicate tasks in cluttered and/or unstructured environments, thus overcoming the most limitations of the current lab prototypes for service climbing and mobile robots.

Further information adhesion techniques in general may be found in the works of Longo and Muscato (2008). The widely accepted characterization of locomotion modes in the field of mobile robotics may be found in the work of Yim (1994).

References

Amano, H., Osuka, K., Tarn, T., 2001. Development of vertically moving robot with gripping handrails for fire fighting. In: IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Maui (USA).

Asari, Y., Yanagawa, H., Oshida, T., 2007. Gliding ability of the Siberian flying squirrel Pteromys volans orii. Mamm. Study 32 (4), 151–154.

Asbeck, A.T., Kim, S., McClung, A., Parness, A., Cutkosky, M.R., 2006. Climbing walls with microspines. In: IEEE ICRA, Orlando, FL, USA.

Astley, H.C., Jayne, B.C., 2007. Effects of perch diameter and incline on the kinematics, performance and modes of arboreal locomotion of corn snakes (*Elaphe guttata*). J. Exp. Biol. 210, 3862–3872.

Astley, H.C., Jayne, B.C., 2009. Arboreal habitat structure affects the performance and modes of locomotion of corn snakes (*Elaphe guttata*). J. Exp. Zool. 311A, 207–216.

Balaguer, C., Pastor, J., Gimenez, A., Padron, V., Abderrahim, M., 1998. Roma: a multifunctional autonomous self-supported climbing robot for inspection application. In: Third IFAC Symposium on Intelligent Autonomous Vehicles, Madrid (Spain).

Balaguer, C., Giménez, A., Abderrahim, M., 2002. ROMA robots for inspection of steel based infrastructures. Ind. Robot 29 (3), 246–251.

Bertram, J., 2004. New perspectives on brachiation mechanics. Am. J. Phys. Anthropol 125 (S39), 100–117.
Bonaccorso, F., Bruno, C., Longo, D., Muscato, G., 2008. Structure and model identification of a vortex-based suction cup. In: Proceedings of the 11th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR), Coimbra (Portugal).
Busko, K., Klossowski, M., 1998. Muscle torque of male basketball players playing at different floor positions. In ISBS-Conference Proceedings Archive, vol. 1, No. 1, Konstanz, Germany.
Byrnes, G., Lim, N.T.-L., Spence, A.J., 2008. Take-off and landing kinetics of a free-ranging gliding mammal, the Malayan colugo (*Galeopterus variegatus*). Proc. R. Soc. B 275, 1007–1013.
Byrnes, G., Libby, T., Lim, N.T., Spence, A.J., 2011. Gliding saves time but not energy in Malayan colugos. J. Exp. Biol. 214, 2690–2696.
Cartmill, M., 1985. Climbing. In: Functional Vertebrate Morphology. Belknap Press, Cambridge, pp. 73–88.
Chang, Y-.H., Bertram, J.E.A., Lee, D.V., 2000. The external forces and torques generated by the brachiating white-handed gibbon (Hylobates lar). Am. J. Phys. Anthropol. 113, 201–216.
Chen, S., Shang, J., Zhao, Z., Sattar, T., Bridge, B., 2006. Novel solutions to design problems of industrial climbing robots. In: Climbing and Walking Robots. Proceedings of the Eighth International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR 2005). Springer, Berlin, Heidelberg, pp. 139–146.
Clark, J.E., Dickson, J.D., 2013. Design of a multimodal climbing and gliding robotic platform. Trans. Mechatron. 18 (2), 494–505.
Clark, J., Goldman, D., Lin, P.-C., Lynch, G., Chen, T., Komsuoglu, H., Full, R., Koditschek, D., 2007. Design of a bio-inspired dynamical vertical climbing robot. In: Robotics: Science and Systems.
Clauser, C.E., McConville, J.T., Young, J.W., 1969. Weight, volume and center of mass of segments of the human body. Tech. Rep. AMRL TR 69–70, Wright Patterson Air Force Base, Ohio (NTIS No. AD-710 622).
Degani, A., Shapiro, A., Choset, H., Mason, M.T., 2007. A dynamic single actuator vertical climbing robot. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2007.
Dickson, J.D., Patel, J., Clark, J.E., 2013. Towards maneuverability in plane with a dynamic climbing platform. In: Robotics and Automation (ICRA), Karlsruhe, Germany.
Electric Power Research Institute, "Snake Robot," 2010. [Online]. Available: http://transsensorsrobots.epri.com/snake-robot.html. (accessed 01.06.13).
Ellem, G.K., Furst, J.E., Zimmerman, K.D., 2002. Shell clamping behaviour in the limpet *Cellana tramoserica*. J. Exp. Biol. 205, 539–547.
Fukuda, T., Hosokai, H., Kondo, Y., 1991. Brachiation type of mobile robot. In: Fifth International Conference on Advanced Robotics (ICAR 1991).
Fukuda, T., Doi, M., Hasegawa, Y., Kajima, H., 2006. Multi-locomotion control of biped locomotion and brachiation robot. In: Fast Motions in Biomechanics and Robotics.pp. 121–145.
Galvao, R., Song, A., Tian, X., Bishop, K., Swartz, S., Breuer, K., 2006. The aerodynamics of compliant membrane wings modeled on mammalian flight mechanics. In: American Institute Aeronautics Astronautics Meeting, San Francisco, CA.
Gorb, S., 2001. Attachment Devices of Insect Cuticle. Kluwer Academic Publishers, Dordrecht.

Gorb, S., 2005. Uncovering insect stickiness: structure and properties of hairy attachment devices. Am. Entomol, 31–35.

Gorb, S.N., Sinha, M., Peressadko, A., Daltorio, K.A., Quinn, R.D., 2007. Insects did it first: a micropatterned adhesive tape for robotic applications. Bioinspir. Biomim. 2, S117–S125, Biomimetic technologies: volume 1—materials and sensors.

Graber, L., 2012. Master Thesis—Self-Contained High Payload Robot for Climbing on Multiple Vertical Environments, Zurich.

Guarnieri, M., Debenest, P., Inoh, T., Takita, K., Masuda, H., Kurazume, R., Fukushima, E., Hirose, S., 2009. HELIOS carrier: tail-like mechanism and control algorithm for stable motion in unknown environments. In: IEEE International Conference on Robotics and Automation, ICRA 2009.

Haynes, G.C., Khripin, A., Lynch, G., Amory, J., Saunders, A., Rizzi, A.A., Koditschek, D.E., 2009. Rapid pole climbing with a quadrupedal robot. In: IEEE International Conference on Robotics and Automation (ICRA), Kobe, Japan.

Hillenbrand, C., Schmidt, D., Berns, K., 2008. CROMSCI—a climbing robot with multiple sucking chambers for inspection tasks. In: Proceedings of The 11th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR), Coimbra (Portugal).

Hopkins, J.K., Spranklin, B.W., Gupta, S.K., 2009. A survey of snake-inspired robot designs. Bioinspir. Biomim. 4(2).

Ishigure, Y.H.K., Kawasaki, H., 2013. A pruning robot with a power-saving chainsaw drive. In: 2013 IEEE International Conference on Mechatronics and Automation (ICMA), Takamatsu.

Jayne, B.C., 1982. Comparative morphology of the semispinalis-spinalis muscle of snakes and correlations with locomotion and constriction. J. Morphol. 172, 83–96.

Kajima, H., Hasegawa, Y., Fukuda, T., 2003. Learning algorithm for a brachiating robot. Appl. Bionics Biomech. 1 (1), 57–66.

Kajima, H., Doi, M., Hasegawa, Y., Hasegawa, Y., 2004. A study on a brachiation controller for a multi-locomotion robot—realization of smooth, continuous brachiation. Adv. Robot. 18 (10), 1025–1038.

Kawasaki, H., Murakami, S., Kachi, H., Ueki, S., 2008. Novel climbing method of pruning robot. In: IEEE SICE Annual Conference 2008.

Kim, S., Asbeck, A., Cutkosky, M., Provancher, W., 2005. SpinybotII: climbing hard walls with compliant microspines. In: International Conference on Advanced Robotics, Washington (USA).

Lam, T.L., Xu, Y., 2012. State-of-the-art tree-climbing robots. In: Tree Climbing Robot, 78, Springer, Berlin, Heidelberg, pp. 5–8.

Libby, T., Moore, T.Y., Chang-Siu, E., Li, D., Cohen, D.J., Jusufi, A., Full, R.J., 2012. Tail-assisted pitch control in lizards, robots and dinosaurs. Nature 481, 181–184.

Longo, D., Muscato, G., 2008. Adhesion techniques for climbing robots: state of the art and experimental considerations. In: Plenary Talk at the 11th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR), Coimbra (Portugal).

McGuire, J.A., Dudley, R., 2005. The cost of living large: comparative gliding performance in flying lizards (Agamidae: Draco). Am. Nat. 166, 93–106.

McGuire, J.A., Dudley, R., 2011. The biology of gliding in flying lizards (genus *Draco*) and their fossil and extant analogs. In: Biomechanics and Behavior Gliding Flight, Salt Lake City, UT.

McKenna, J.C., Anhalt, D.J., Bronson, F.M., Brown, H.B., Schwerin, M., Shammas, E., Choset, H., 2008. Toroidal skin drive for snake robot locomotion. In: 2008 IEEE International Conference on Robotics & Automation, Pasadena, California.

Miyake, T., Ishihara, H., Yoshimura, M., 2007. Basic studies on wet adhesion system for wall climbing robots. In: IEEE/RSJ International Conference on Intelligent Robots and Systems IROS 2007, San Diego, California, USA.

Murphy, M., Sitti, M., 2009. Waalbot: agile climbing with synthetic fibrillar dry adhesives. In: IEEE International Conference on Robotics and Automation (ICRA), Kobe (Japan).

Norberg, U., 1985. Evolution of vertebrate flight: an aerodynamic model for the transition from gliding to active flight. Am. Nat. 126, 303–327.

Osswald, M., Iida, F., 2011. A climbing robot based on hot melt adhesion. In: IEEE International Conference on Intelligent Robots and Systems (IROS 2011), San Francisco.

Pchelkin, S., Shiriaev, A.S., Mettin, U., Freidovich, L.B., Aoyama, T., Lu, Z., Fukuda, T., 2011. Shaping energetically efficient brachiation motion for a 24-DOF gorilla robot. In: 2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), San Francisco, CA.

Provancher, W.R., Jensen-Segal, S.I., Fehlberg, M.A., 2011. ROCR: an energy-efficient dynamic wall-climbing robot. Trans. Mechatron. 16 (5), 897–906.

Riskin, D.K., Racey, P.A., 2010. How do sucker-footed bats hold on, and why do they roost head-up? Biol. J. Linn. Soc. 99, 233–240.

Riskin, D.K., Bahlman, J.W., Hubel, T.Y., Ratcliffe, J.M., Kunz, T.H., Swartz, S.M., 2009. Bats go head-under-heels: the biomechanics of landing on a ceiling. J. Exp. Biol. 212, 945–953.

Rollinson, D., Ford, S., Brown, B., Choset, H., 2013. Design and modeling of a series elastic element for snake robots. In: ASME Dynamic Systems and Controls Conference, Stanford, CA.

Russell, A.P., Dijkstra, L.D., 2001. Patagial morphology of *Draco volans* (Reptilia: Agamidae) and the origin of glissant locomotion in flying dragons. J. Zool. 253, 457–471.

Saito, F., Fukuda, T., 1996. A first result of the brachiator III—a new brachiation robot modeled on a siamang. In: Artificial Life V.

Santos, D., Heyneman, B., Sangbae, K., Esparza, N., Cutkosky, M.R., 2008. Gecko-inspired climbing behaviors on vertical and overhanging surfaces. In: IEEE International Conference on Robotics and Automation, ICRA 2008. Pasadena, CA, USA.

Shapiro, A., Mahpoda, I., Zuk, H., 2005. A snail inspired wall climbing robot for counter terrorism duty. In: The 30th Israeli Conference on Mechanical Engineering, Tel-Aviv Israel.

Smith, A.M., 1991. The role of suction in the adhesion of limpets. J. Exp. Biol. 161, 151–169.

Smith, A.M., 1992. Alternation between attachment mechanisms by limpets in the field. J. Exp. Mar. Biol. Ecol. 160 (2), 205–220.

Socha, J.J., Miklasz, K., Jafari, F., Vlachos, P.P., 2010. Non-equilibrium trajectory dynamics and the kinematics of gliding in a flying snake. Bioinspir. Biomim. 5, 1–12.

Tavakoli, M., Zakerzadeh, M., Vossoughi, G., Bagheri, S., 2005. Design and prototyping of a hybrid pole climbing and manipulating robot with minimum DOFs for construction and service applications. In: Climbing and Walking Robots: Proceedings of the Seventh International Conference Clawar 2004, Madrid (Spain).

Tavakoli, M., Marques, L., de Almeida, A.T., 2008. A comparison study on pneumatic muscles and electrical motors. In: IEEE International Conference on Robotics and Biomimetics ROBIO 08, Bangkok, Thailand.

Tavakoli, M., Marques, L., Bonsignorio, F., 2010a. Biomimetic inspiration in climbing robots. In: CLAWAR 2010.

Tavakoli, M., Marques, L., de Almeida, A.T., 2010b. Development of an industrial pipeline inspection robot. Ind. Robot. Int. J. 37 (3), 309–322.

Thorington, R.W., Darrow, K., Anderson, C.G., 1998. Wing tip anatomy and aerodynamics in flying squirrels. J. Mammal. 79, 245–250.

Transeth, A.A., Pettersen, K.Y., Liljebäck, P., 2009. A survey on snake robot modeling and locomotion. Robotica 27 (07), 999–1015.

Trimmer, B., Takesian, A., Sweet, B., Rogers, C., Hake, D., Rogers, D., 2006. Caterpillar locomotion: a new model for soft-bodied climbing and burrowing robots. In: Seventh International Symposium on Technology and the Mine Problem (vol. 1, pp. 1–10), Monterey, CA.

Unver, O., Uneri, A., Aydemir, A., Sitti, M., 2006. Geckobot: a gecko inspired climbing robot using elastomer adhesives. In: IEEE International Conference on Robotics and Automation, ICRA 2006, Orlando, Florida, USA.

Usherwood, J.R., Bertram, J.E.A., 2003. Understanding brachiation: insight from a collisional perspective. J. Exp. Biol. 206 (10), 1631–1642.

Usherwood, J.R., Larson, S.G., Bertram, J.E.A., 2003. Mechanisms of force and power production in unsteady ricochetal brachiation. Am. J. Phys. Anthropol. 120 (4), 364–372.

Wang, W., Wang, Y., Wang, K., Zhang, H., Zhang, J., 2008. Analysis of the kinematics of module climbing caterpillar robots. In: IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM 2008, pp. 84–89.

Wang, L., Neuschaefer, F., Bernet, R., Iida, F., 2012. Design considerations for attachment and detachment in robot climbing with hot melt adhesives. In: IEEE International Conference on Robotics and Automation (ICRA 2012), St. Paul, USA.

Wang, L., Graber, L., Iida, F., 2013. Large-payload climbing in complex vertical environments using thermoplastic adhesive bonds. IEEE Trans. Robot. 29 (4), 863–874.

Wang, L., Culha, U., Iida, F., 2014. A dragline-forming mobile robot inspired by spiders. Bioinspir. Biomim. 9(1).

Wright, C., Johnson, A., Peck, A., McCord, Z., Naaktgeboren, A., Gianfortoni, P., Gonzalez-Rivero, M., Hatton, R., Choset, H., 2007a. Design of a modular snake robot. In: IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2007, pp. 2609–2614.

Wright, C., Johnson, A., Peck, A., McCord, Z., Naaktgeboren, A., Gianfortoni, P., Gonzalez-Rivero, M., Hatton, R., Choset, H., 2007b. Design of a modular snake robot. In: 2007 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems, San Diego, CA, USA.

Wright, C., Buchan, A., Brown, B., Geist, J., Schwerin, M., Rollinson, D., Tesch, M., Choset, H., 2012. Design and architecture of the unified modular snake robot. In: 2012 IEEE International Conference on Robotics and Automation, St. Paul, MN.

Yim, M., 1994. A taxonomy of locomotion. In: Chapter 3 of the PHD Thesis, Locomotion with a unit-modular reconfigurable robot, at the department of mechanical engineering of Stanford University.

Yim, M., Homans, S., Roufas, K., 2001. Climbing with snake-like robots. In: IFAC workshop on mobile robot technology, pp. 21–22.