

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

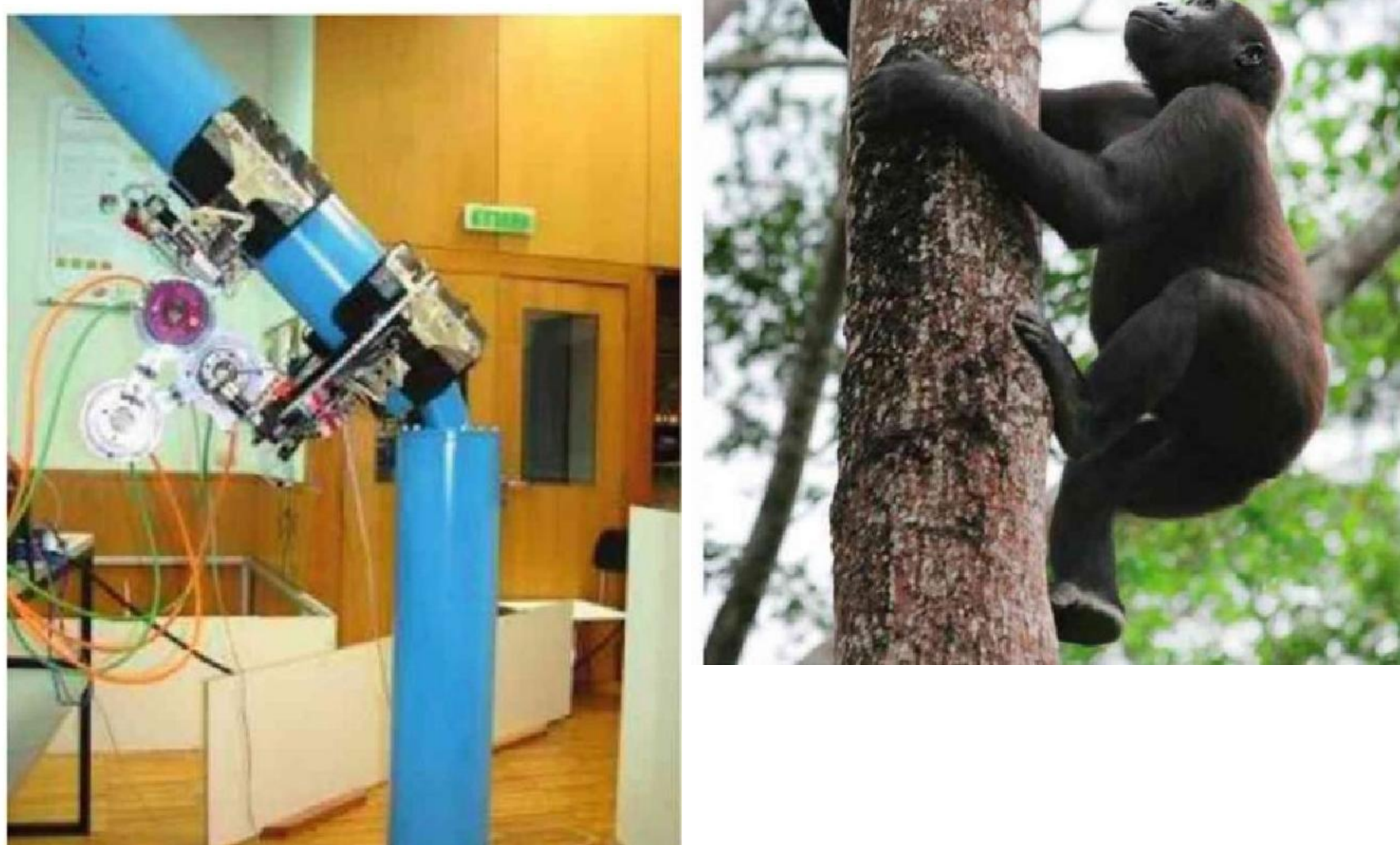


Figure 14.1 3D Climber robot (on the left), developed at the University of Coimbra, is a step-by-step climbing robot which draws inspiration from the climbing and gripping techniques of primates, shown on the right image.

(Image courtesy of Hagit Berkovich.)

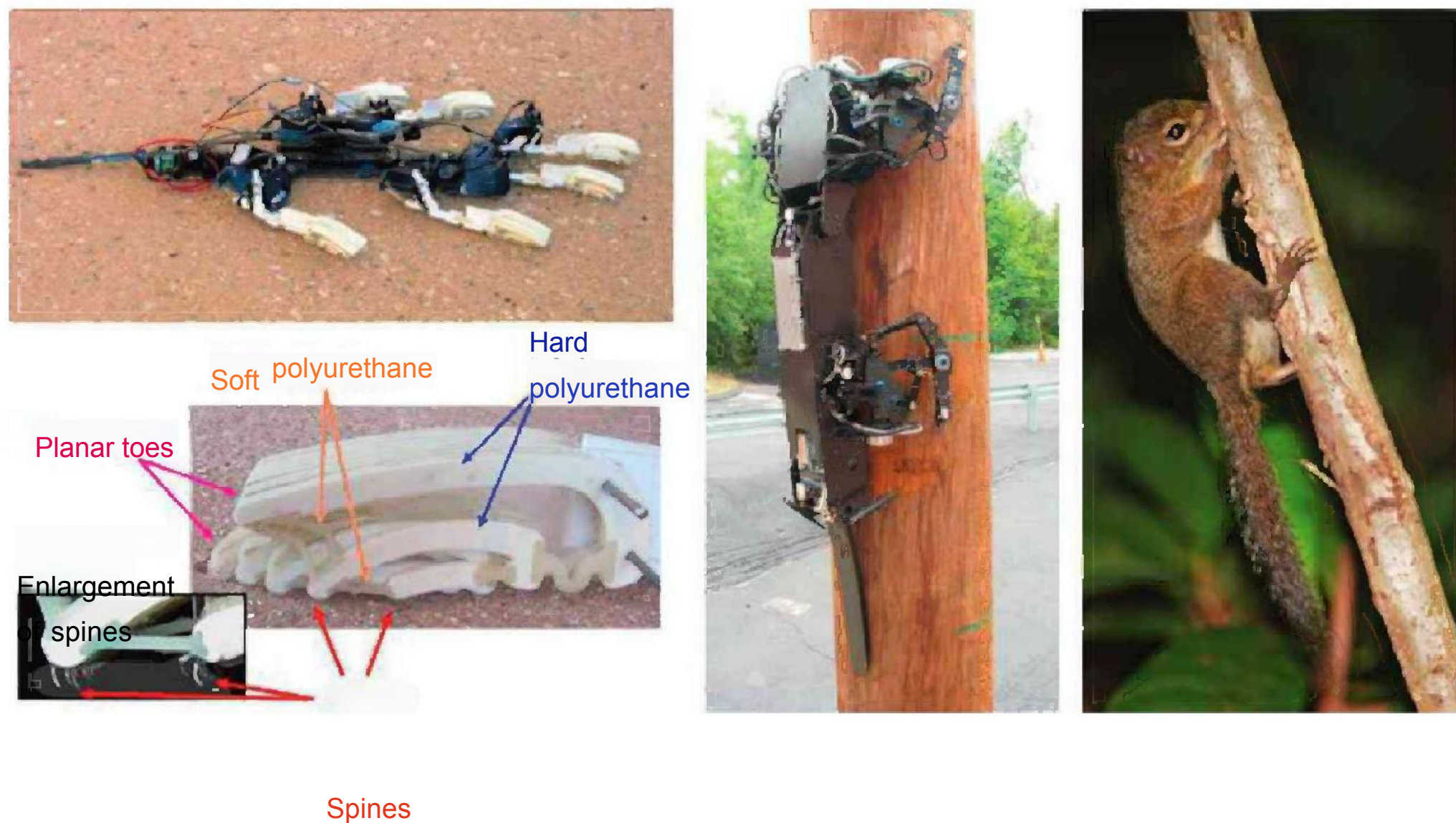


Figure 14.2 SpinyBot (on the left) developed at Stanford uses a novel patented technology that enables it to climb smooth, rough, uneven, porous, and dirty surfaces using arrays of small spines, which hook onto bumps and pits on the surface. In the center is the RiSE V3, another example of the use of 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.

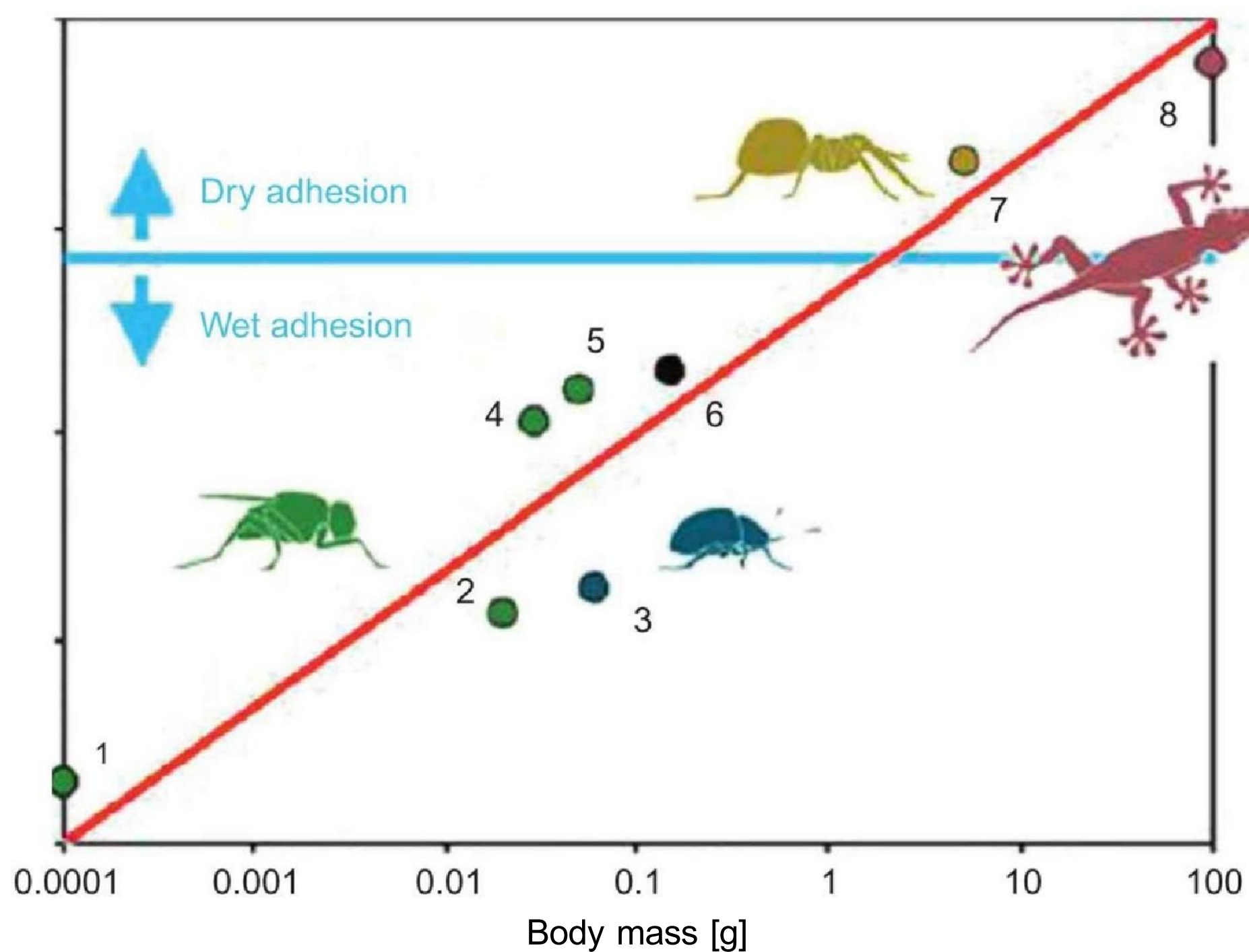


Figure 14.3 Adhesion mechanism according to body mass, for small animals. 1, 2, 4, 5: flies; 3: beetle; 6: bug; 7: spider; 8: geckonid lizards. Adapted from the book "Attachment Devices of Insect Cuticle" by Gorb (2001) and taken from Gorb et al. (2007) © IOP Publishing.

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

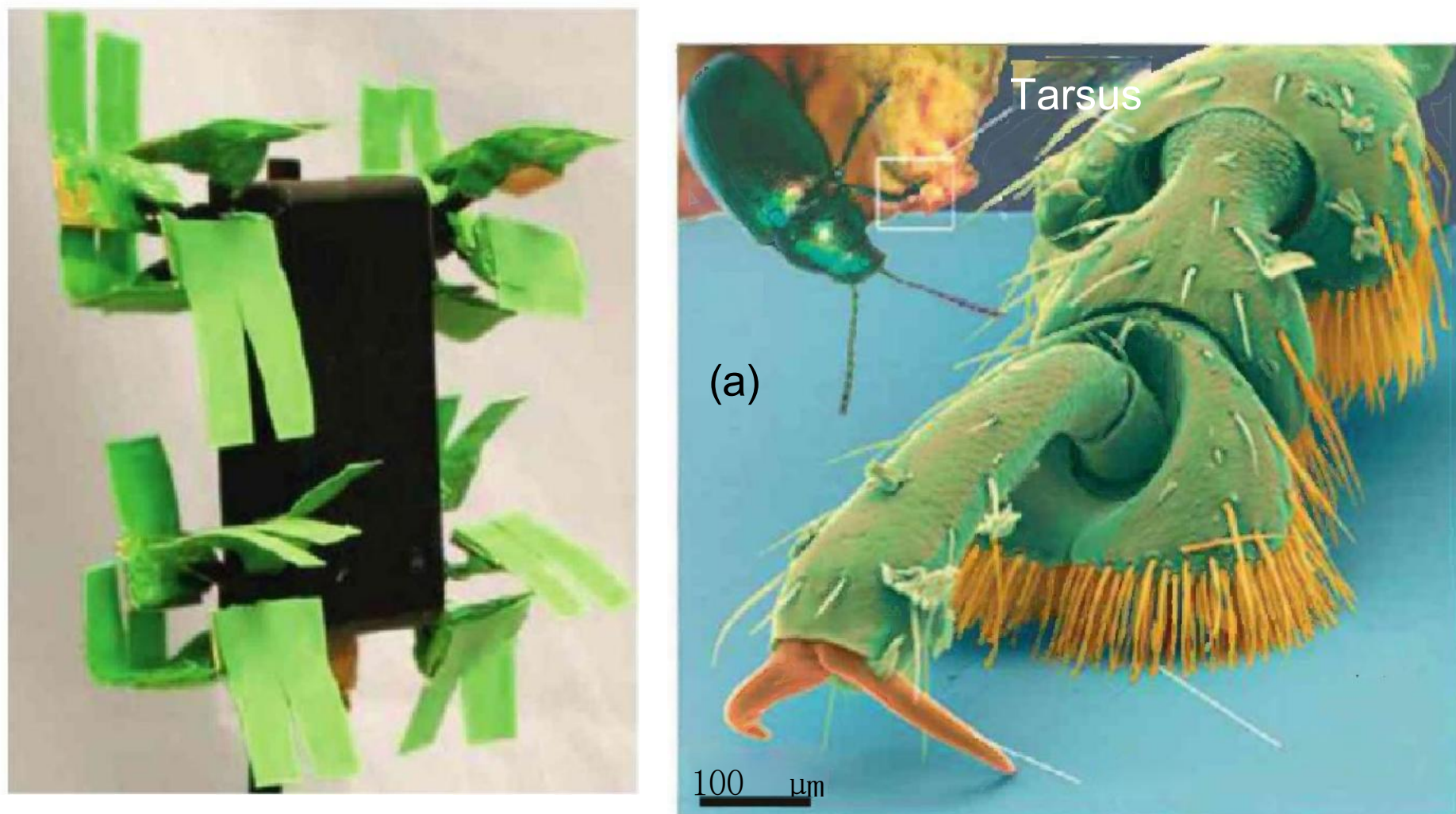


Figure 14.5 On the left, the Mini-WhegsTM wet adhesive pad climbing robot and on the right an example of the hairy attachment system (taken from Gorb et al. (2007) IOP Publishing.

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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, Tübingen, 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-WhegsTM (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 secrete 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.

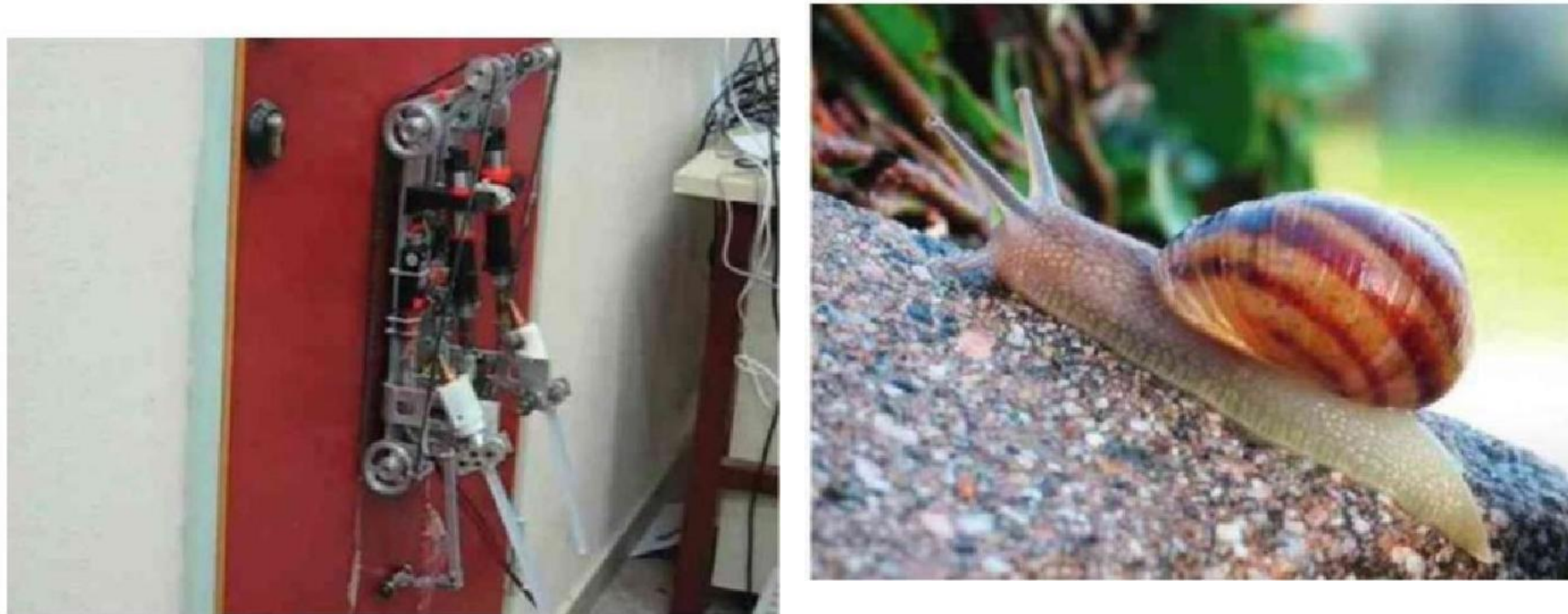


Figure 14.7 The snail-inspired wall climbing robot uses the same adhesion mechanism as a snail, by releasing a viscous glue fluid which acts as glue.
(Snail photo by John D.)

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. 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-II. 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 I.” 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 weighs 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 (Javne, 1982). While moving in arboreal habitats, snakes move slowly along bare branches in the form of

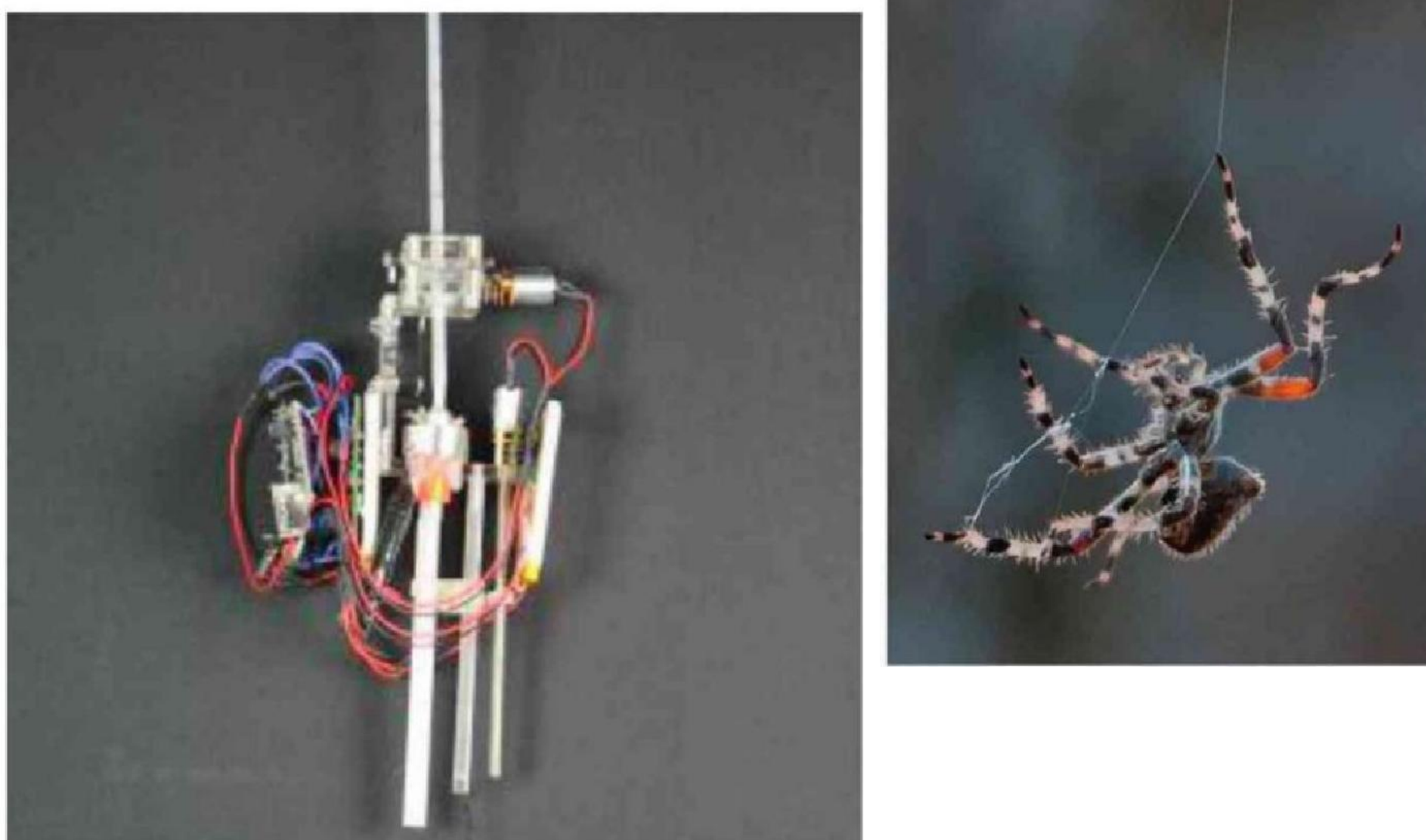


Figure 14.9 The ETH dragline-forming mobile robot, on the right, draws inspiration from spiders (spider photo credit: Stevie Benintende, www.whatsteviesees.com).

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 (Traneth 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.

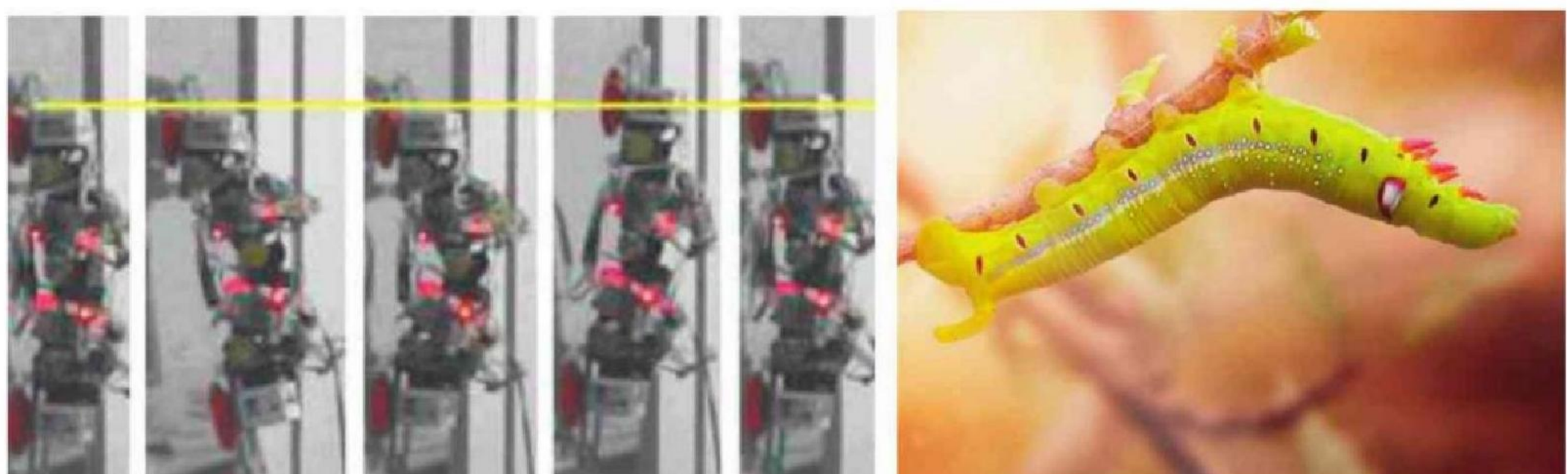


Figure 14.11 The caterpillar robot by Wei Wang et al., on the left, climbs walls using the crawling principles of caterpillars.

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