Biologically Inspired Mobile Robots

Dennis Hong, University of California, Los Angeles

Biologically inspired robots or biomimetic robots are robots that are designed by seeking design solutions from nature to replace the classical engineering solutions. Biomimetics does not mean simply copying and reproducing the mechanisms from nature, but rather applying the key principles of biology to robotics with novel engineering solutions through studying and observing nature. This requires a deep understanding of the nature's key principles and translating them into engineering design, and developing novel fabrication techniques and actuation methods. Biomimetics is a broad field that covers all ranges of robotics from robot structure, actuator, sensors and intelligence. However, this paper focuses on the mechanism design of biologically inspired ground mobile robots. Also, we exclude "walking" or "jumping" robots in the scope of this paper, as this topic is extensive enough to be covered in a separate paper.

1. Biologically Inspired Robot Design Approach

The various locomotion methods in nature have inspired robots to mimic them to overcome various obstacles in the environment and move around with extreme agility. Instead of using wheels, most of the animals in nature use legs of different sizes and numbers; humans have two legs, many animals have four legs and insects have various numbers of legs. Snakes and worms move around without legs by creating waves with their body. These movements are based on the actuator of nature, the muscle. Muscles create linear motion and the structures of the animal are fitted to these linear motions.

Depending on the size of the species the optimal mode of locomotion and their structure varies. For example, jumping is used often for small insects to escape danger, since their small size makes it hard for them to escape quickly. Larger insects or animals tend to run or crawl to escape the danger, as they are ineffective in jumping large distances due to their large mass. Thus size has a significant impact on the approach when designing biologically inspired robots. As such, biomimetic robot design starts from understanding the nature and the advantage of that principle in an engineering viewpoint.

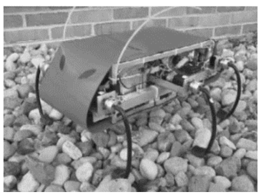
Nature's biological structures are composed of various materials such as tissues, bones, cuticles, flesh, and feather. For robots, these materials are replaced with engineered materials such as metal, polymers, and composites. Large robots tend to be better built with conventional mechanical components such as motors, joints and linkages made of metal. However, as the robot becomes smaller, it becomes challenging as conventional mechanical components become ineffective, due to friction and other inefficiencies.

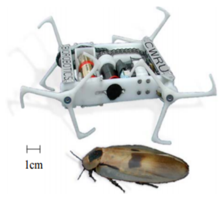
2. Ground Mobility Mechanisms

Inspired by nature, there has been a number of successful ground mobility mechanisms for robots developed over the decade. The following is a survey of some examples of biologically inspired ground mobile robots that crawl with legs, crawl like worms, undulate like snakes, or climb.

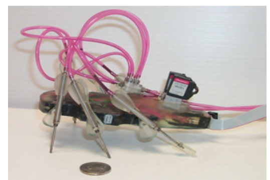
2.1 Crawling with Legs

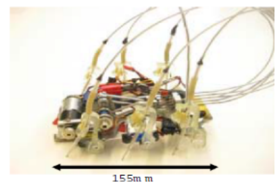
One of the most impressive animals in nature that is capable of maintaining stability during locomotion even at high speeds is the cockroach. Some types of cockroaches can even achieve speeds of up to 50 body length per second, and can crawl uneven terrain with high obstacles much higher than their heights [1]. Inspired by this, RHex, a hexapod crawling robot with a C shaped legs, is one of the first robots to implement these characteristics [2]. Mini-Whegs [3] has spoke-wheels with 3 spokes each and their gait can passively adapt to the terrain similar to climbing cockroaches [4]. Sprawlita [5] is a hexapod crawling robot that uses pneumatic actuators on each leg and passive rotary joints so that it can achieve dynamic stability. iSprawl [6] uses flexible push-pull cables driven by an electric motor.


(a) RHex



(b) Mini-Whegs


(c) Sprawlita

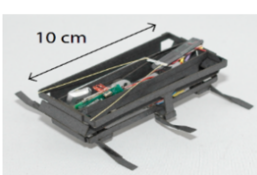


(d) iSprawl

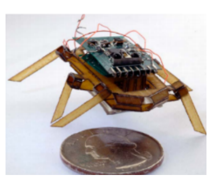
Fig. 1

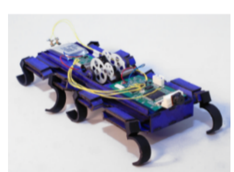
Crawling robots inspired by cockroach (a) RHex, Saranli, Uluc, et al. (b) Mini-Whegs, Morrey, Jeremy M., et al. (c) Sprawlita, Clark, Jonathan E., et al. (d) iSprawl, S. Kim, et al.

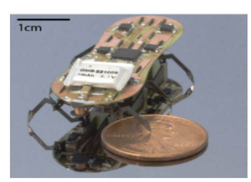
Mimicking the locomotion mode of a cockroach can especially improve the performance of millimeter or centimeter scale crawling robots as they face in-efficiency using conventional mechanisms. Weighing 16.2g, DASH [7] is fabricated using the SCM (Smart composite manufacturing) process, and can achieve a speed up to 15 body length/s. This robot has only one electric motor but uses four-bar linkages to generate the crawling gait. Weighing only 2.4g, RoACH [8] is a hexapod crawling robot that imitates the alternating tripod gait. It uses 2 SMA wire actuators which let the body contract in two orthogonal directions, and can crawl 1 body length/s. Weighing 35g, OctoRoACH [9] has 8 legs driven by 2 motors so that it maximizes pitch stability. HAMR3 [10] uses 9 piezoelectric actuators. Each leg performs the swing and lift motion through two decoupled piezoelectric actuators through four-bar and slider-crank mechanisms and a spherical five-bar mechanism. HAMR3 weighs 1.7g and has a speed up to 0.9 body lengths/s.



(a) DASH


(b) RoACH


(c) OctoRoACH



(d) HAMR3

Fig. 2
Crawling robots inspired by cockroach. (a) DASH, Birkmeyer, P., et al. (b) RoACH, Aaron M. Hoover, et al. (c) OctoRoACH, Pullin, Andrew O., et al. (d) HAMR3, Baisch, Andrew T., et al.

2.2 Worm-like Crawling

The worm-like crawling motion can be categorized into two types: peristaltic crawling and two anchor crawling. The schematic of how peristaltic locomotion works is shown in Fig. 3. By sequentially changing the volume of the body, the whole body structure is used to generate the motion. Robots that utilize this mode of locomotion have the potential to be used at a collapsed disaster site or inside of pipes for inspection tasks as it can move through small tunnels and in limited spaces like the earthworm. The key design issue in mimicking peristaltic motion is how to create the sequential volume change. Many researchers have tried various creative methods to solve this problem.

A. S. Boxerbaum et al. [11] built a robot with a mesh structure which uses a single motor and wires to make partial volume change to realize a crawling motion. S. Seok et al. [12] used a shape memory alloy (SMA) coil spring actuator with a mesh body structure to change the segmented volume. A. Menciassi et al. [13] also used a SMA coil spring actuator, but implemented micro hooks to increase the friction force for better traction.

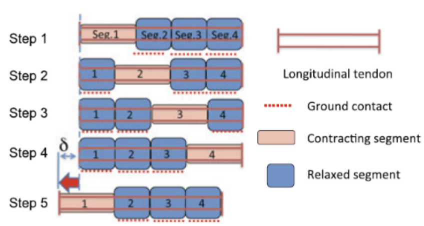


Fig. 3
Peristaltic locomotion [11]

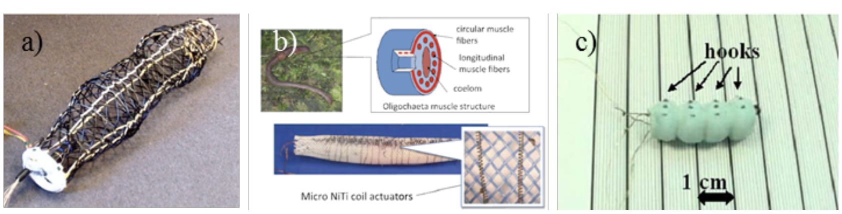


Fig. 4
Peristaltic crawling robots (a) Robot with peristaltic motion, A. S. Boxerbaum et al. (b) Meshworm robot, S. Seok et al. (c) Biomimetic miniature robotic crawler, A. Menciassi et al.

The two anchor crawling method used by the inchworm. Though not fast, it can overcome complicated topology. With an appropriate gripping method, it not only can climb vertical walls, but also can cross the gap. There are two the key design issues for implementing a two anchor crawling motion: first, how to change the shape of the waist and second, how to anchor and unanchor the body to the surface. K. Kotay et al. [14] simply used an electric motor to actuate the waist and used an electromagnetic pad as the anchoring method to climb steel structures (Fig. 5 (a)). N. Cheng et al. [15] used a tendon driven mechanism with a compressible body and anisotropic friction pads for the robot (Fig. 5 (b)). Thermally activated, symmetrical or unsymmetrical compression of the waist joint enabled the robot to steer and crawl forward. J. S. Koh et al. [16] used SMA coil spring actuators to make a waist motion of a body made with a single sheet of glass fiber composite (Fig. 5 (d)). The folding pattern on the sheet enabled a steering motion. H. Lin et al. [17] realize a robot with two anchoring motion, and added a rolling locomotion to solve the speed limitation problem of the two anchor locomotion (Fig. 5 (e)). T. L. Lam et al. [18] developed a robot that uses a backbone rod and an electrical motor to generate the waist motion and to position the anchoring point. (Fig. 5 (c)).

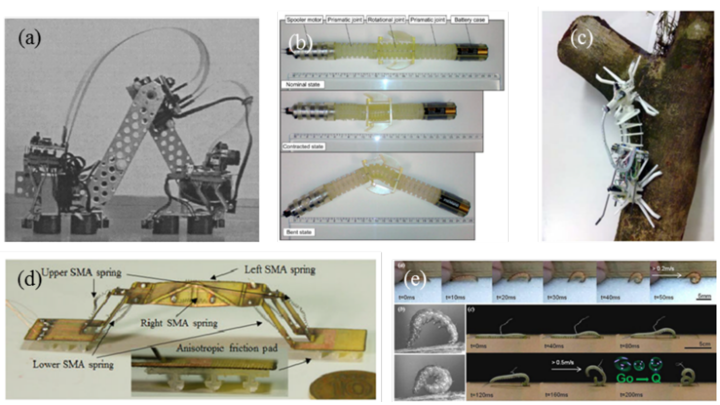


Fig. 5
Two anchor crawling robots (a) The inchworm robot, K. Kotay et al. (b) The soft mobile robot with thermally activated joint, N. Cheng et al. (c) Treebot, T. L. Lam et al. (d) Omega shaped inchworm inspired crawling robot, J. S. Koh et al. (e) GoQBot, H. Lin et al.

2.3 Snakelike Robots

Snakes are limbless, slender and flexible and their locomotion gives them adaptability and mobility through land, uneven ground, narrow channel, pipes, and even water [19]. Locomotion of snake could be efficient compared to legged animals, because there is no lifting of the center of gravity or acceleration of limb parts [20]. Locomotion of the snake like robots can be categorized as the following different types: serpentine motion; sinus lifting; pedal wave; side-winding; spiral swimming; lateral rolling; lateral walking; mixture lean serpentine; and lift rolling motions.
In 1970s, S. Hirose [21] developed a continuous locomotion model and a snake like robot called 'Active Cord Mechanism' (ACM). In 1972, ACM-III [21] was developed

and it was the first robot that could mimic the serpentine motion of real snakes. The first generation of snake like robots could only display planar motion. Then, snake like robot could go upward within narrow pipes and can climb and hold trees [22]. To overcome high above ground obstacles, some robots added actuation parts between each joint [23]. Some snake like robots can swim in the water with spiral and sinusoidal locomotion [21].

Today, mechanism design of snake like robots can be classified with following five different types: active bending joint type; active bending and elongation joint type; active bending joint and active wheel type; passive bending joint and active wheel type; and active bending joint and active crawler type [24]. Most of the snake like robots of today are equipped wheels that are actively or passively driven. Wheel-less snake like robots move with undulatory motion, especially lateral undulation that could be observed in real snakes [24]. Some snake like robots are actuated with smart actuators, such as shape memory alloy or IPMCs, rather than motors.

Since the shape change of the robot body generates the propulsion, tilt sensors, accelerometers, gyroscope, and joint angle sensors become important in controlling the robot [20]. As the body of the robot makes direct contact with the surface, tactile sensors also play an important role. They can also be used for grasping objects like real snakes. One of the challenges is, due to its high degrees of freedom, designing a controller is not easy even for the flat surface locomotion. [20].

Fig. 6

Three snake like robots. (a) AMC-III, Shigeo Hirose (b) Modular snake robot, Howie Choset. (c) AMC-R5, Shigeo Hirose

2.4 Climbing

Climbing insects and animals inspired many researchers to develop robots that can climb and maneuver on vertical surfaces. Some early approaches used suction cups, magnets or sticky adhesives to implement climbing, and more recently claws, spine and sticky pads inspired by nature are being implemented. Insects and reptiles use small spines that catch on fine asperities. Geckos and some spiders employ large numbers of very fine hairs that achieve adhesion.

Some of the robots developed early in the 1990s include, Ninja-1, RAMR, and REST. Ninja-1's [25] main mechanism consists of a 3D parallel link, conduit-wire-driven parallelogram, and valve-regulated multiple suckers. RAMR [26] used underactuation to remove the redundant actuators to drive the small two-legged robot. REST [27] used four legs with electromagnets to climb ferromagnetic walls to perform cleaning, inspection, welding tasks for shipbuilding applications.

For compact climbing robots, mostly developed for reconnaissance purpose, use biomemetics such as imitating spines of climbing insect and cockroach, such as Spinybot [28] and RiSE [29, 30]. These robots can climb hard vertical surfaces including concrete, brick, stucco and masonry with compliant microspine arrays. Insects and geckos can provide inspiration for novel adhesive technology and for the locomotory mechanisms employed during climbing. Mini-Whegs™, Geckobot, Stickybot, Waalbot are typical robots taken advantage of these findings.
Mini-Whegs™ [31] uses wheel-legs with compliant, adhesive feet for climbing locomotion, using adhesive material such as Scotch® tape and later using a novel, reusable insect-inspired polymer (polyvinylsiloxane). Geckobot [32, 33] has kinematics similar to a gecko's climbing gait. It uses a novel peeling mechanism of the elastomer adhesive pads, steering mechanisms and an active tail for robust and agile climbing. Stickybot [34] climbs smooth vertical surfaces such as glass, plastic, and ceramic tile at 4 cm/s. The robot employs several design principles adapted from the gecko including a hierarchy of compliant structures, directional adhesion. The undersides of Stickybot's toes are covered with arrays of small, angled polymer stalks which readily adhere when pulled tangentially from the tips of the toes toward the ankles. When pulled in the opposite direction, they release.
Some other different approaches include using electroadhesion and pendulous climbing. Electroadhesive robots use a novel clamping technology called compliant electroadhesion which controls adhesion electrically using electrostatic charges. It can produce large clamping forces that are around 0.2-1.4N by 1 square centimeter of clamp area, depending on the substrate.

3. Conclusions

Engineers and scientists have been solving difficult problems in robot design by studying and observing nature, and applying nature's key principles and translating them into engineering design. Instead of just trying to copy that of nature, with a deep understanding of the nature's principles and the right approaches of applying them, biomimetics has resulted in a number of very successful ground mobile robots. More recently, the direction is shifting to using more soft materials. This soft robotics poses new challenges in design, control, actuation, and fabrication.

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