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Chapter 1
Introduction

The movements of various animals in nature have evolved over thousands of years. These movements are usually related to where they live, how they obtain food and how they escape from predation. Survival pressures force animals to move from one place to another in an efficient manner. Their movements therefore require reasonable coordination of articulation, so that animals can overcome friction and gravity and push themselves forward. As a branch of animal locomotion classification, limbless locomotion exhibits its unique movement patterns and good performance in specific environments. In this chapter, we explore limbless locomotion in nature and their replica applied to limbless robotics for various applications, and present the necessary functional integration for achieving bio-inspired locomotion control of limbless robots.

1.1 Limbless Locomotion in Nature

There are thousands of animals that can move without limbs or with little help of limbs, such as snakes, worms, caterpillars and fishes. Surprisingly, they have exhibited a wide range of locomotive capabilities, including serpentine creeping, peristaltic crawling and anguilliform swimming. These limbless animals, due to lack of legs, use their bodies to generate movements. They propagate flexural waves along the length of their bodies, so that the force generated between them and the surrounding environment can propel them forward.

We can observer various limbless locomotion in the animal kingdom. For example, in the desert a snake uses sidewinding, a sideway type of locomotion, to avoid overheating when excessive contacting with the desert sand. During sidewinding, the snake moves diagonally, in which its head first lifts off and laterally sets down a short distance away, and then the body follows the head sequentially. In theory, the movement can be derived from superimposing of a vertical body wave on a lateral

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undulation. Beside sidewinding, snakes can perform lateral undulation, concertina locomotion and rectilinear locomotion and their combinations to adapt to environmental changes (Jayne 1986).

Another example is caterpillar locomotion. Different from snake locomotion via pure body undulation, caterpillars utilize prolegs to grip the substrate and pull the legs forward sequentially to form locomotion (Van Griethuijsen and Trimmer 2014). Depending on the strategy of leg sequence, caterpillars can perform several types of locomotion, such as inching and crawling. The former is often seen in small caterpillars. They move the most posterior legs forward and use them as an anchor to form an Ω body shape, then release the front legs and stretch the body forward to complete the inching step. Crawling is more often seen in bigger caterpillars. Their legs will be lifted and anchor one step forward in sequence, resulting in a body wave propagating from rear to head. Special locomotion strategies exist when caterpillars get threatened. For example, they can launch and bend the body into a wheel, and take advantage of momentum to move backward to escape away from danger (Brackenbury 1997).

Fish is also able to generate movements via body undulation. This is achieved by contracting one side of body muscles while relaxing body muscles from the other side (Lauder 2015). The undulation movement passes on momentum to the water, and the reaction force in turn propel the fish forward. Although the way of propulsion is in principle not the same as that of snake motion, i.e., using friction force, both motions exhibit body wave propagation from head to tail. Fish movements have a general form of body wave, but differ in number of waves, wave speed and undulation amplitude among fish species. In addition to body undulation, fishes use fins for balance and steering during swimming.

In general, compared to other forms of locomotion on land (we omit fish locomotion here), limbless locomotion provides the following advantages in animals (Hopkins et al. 2009):

- Limbless animals have a linear structure with a compact cross-section that allows them to cross through thin holes and gaps.
- For limbless animal on land, they can climb trees, rocks, and any other vertical surface. This is achieved by lifting the front one-third of their bodies up while setting the lower two-thirds of their bodies as a base.
- Their locomotion gaits are very stable. Since they keep most of their bodies in contact with the terrain during locomotion, they have a low center of mass and a large contact area that prevent them from falling over.
- They can act as manipulators when they are clenching prey or twining around tree branches.

We see the limbless morphology brings significant advantages in complex environments; however, how is limbless locomotion produced and adapted to environmental changes? In fact, animals' morphological and physiological behaviors dominate their locomotion patterns (Dickinson et al. 2000). Animals move by stretching and contracting body muscles. However, how animals move, namely how they coordinate body muscles to generate locomotion has not been deeply investigated until the rapid development of modern neuroscience. The key challenge in the study of locomotion is to determine the structure-function relations between the muscular, skeletal and nervous systems. Although physiological phenomena of the generated movements can be analyzed based on electromyographic (EMG), it is still not yet fully understood the underlying mechanisms of the neural circuits in the nervous system.

At the beginning of the 20th century, it was found that locomotion patterns can be produced in spinal cord without any commands coming from the brain. Neurobiological studies of various vertebrates have shown that there is a type of neural circuits called central pattern generators (CPGs) in the spinal cord (Grillner 1985). One the one hand, CPGs can produce rhythmic signals that control muscular activity to generate rhythmic patterns, for example, to adjust the speed of locomotion or to change the length of a stride. On the other hand, CPGs are able to respond to sensory feedback to alter the pattern of locomotion, which help animals to adapt to their surroundings during locomotion.

1.2 Limbless Locomotion in Robots

Motivated by the advantages of limbless locomotion, researchers have been interested in developing limbless robots and applying these movements to their corresponding mechanical counterparts for centuries. The limbless design offers significant benefits for dealing with complex environments where traditional machines with appendages such as wheels or legs fail to traverse. More specifically, limbless robots have several potential advantages over wheeled and legged robots (Dowling 1997):

- **Stability**: Copied from the morphology of limbless animals, limbless robots naturally inherit their configuration features, including distributed body mass, low center of gravity and multiple contact points. Thus there is no need to worry about stability in this kind of robots. In contrast, stability is of great concern to wheeled and legged robots. They suffer an impact with the ground and will fall over if the center of mass moves out of the bounds of contact points.
- **Terrainability**: Wheeled and legged robots are sometimes limited in the type and scale of terrains. While limbless robots are supposed to be able to traverse a wide variety of terrains since they can learn diverse locomotion modes from nature. This feature enables the use of limbless robots in more strict terrains, such as passing through pipes, climbing up and over obstacles, passing terrains with soft grounds.
- **Redundancy**: Limbless robots have redundant designs that repeat simple actuators in sequence many times. The modular approach makes the robotic system somewhat robust that even if one of the actuators fails, the robots are still able to move.

Considering the characteristics of limbless robots, there would be several applications that limbless robots are suitable for, including exploration, inspection, search and rescue, medical treatment and reconnaissance.