Guoyuan Li, Houxiang Zhang, Jianwei Zhang

Bio-inspired locomotion control of Limbless robots

Ålesund, March 2021

Norwegian University of Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

Limbless robots have the potential ability to perform various highly efficient movements in different environments, taking advantage of the features of limbless locomotion, such as a low center of gravity, a large contact area and a distributed mass. This book deals with the locomotion control of limbless robots, concentrating specifically on the study of a hierarchical control architecture as steps toward developing limbless robots capable of 3D locomotion, fast reflex responses and sophisticated responses to environmental stimuli.

First, an overview of limbless robots is presented. Various limbless robots found in the literature are investigated. The survey not only introduces some potential applications for limbless robots, but also establishes a classification of limbless locomotion according to the limbless robots' configurations and auxiliary equipment. Moreover, different approaches to autonomously generate motion patterns for limbless robots are discussed. Based on the survey, We present our first attempt to limbless locomotion using sinusoidal generators and consider that a bio-inspired model, such as the Central Pattern Generator (CPG) could be an superior solution, since it is ideally suited to being applied to a hierarchical control architecture.

Then, a bio-inspired CPG model is proposed. The key problem for developing such a hierarchical control architecture is how to design a CPG based controller that can not only generate various gaits, but also provide a solution for realizing reflex mechanisms as well as integrating sensory feedback. To this end, a CPG model inspired by the neuronal circuit diagram in the spinal cord of swimming lampreys is designed. A set of interneurons described with sigmoid functions and leaky integrators is incorporated into the design of the neural oscillator for rhythmic signal generation. Furthermore, according to the connection between neural oscillators, a chained type and a cyclic type of CPG circuits are developed. The chained type CPG circuit is used for generating traveling waves between oscillators, while the cyclic type CPG circuit is used for producing synchronization and maintenance activities. Through numerical simulations, the control parameters over relevant characteristics of the two types of CPG circuits are studied in detail.

Next, the proposed CPG model is further designed for limbless gait implementation. Considering the configuration of limbless robots with pitch modules and yaw modules connected alternatively, two CPG circuits are applied to the pitch grouped modules and the yaw grouped modules, respectively. Both the necessary conditions for cooperation between the two CPG circuits and the control parameters for fast limbless locomotion are investigated. Four types of limbless gaits, i.e. side winding, rolling, turning and flapping are realized. Results of simulations and experiments show the effectiveness of the proposed CPG circuits in generating limbless locomotion.

After that, in order to realize fast sensory reflex responses, the concept of both

sensory neurons and reflex arcs are utilized. Since the proposed CPG model is derived from neural circuit in the spinal cord of lampreys and the existence of sensory neurons in lampreys has been proven, it is simple and natural to add sensory neurons into the proposed CPG model at the neuronal level. Based on the design of the sensory neurons, a reflex mechanism taking advantage of reflex arcs forms short pathways to bridge external stimuli and the CPG model. Thus fast responses can be made when the external stimuli are afferent to the CPG model. A ball hitting experiment and a corridor passing experiment confirm the feasibility of the reflex mechanism.

Finally, the development of sophisticated responses to environmental stimuli is presented. A framework that combines the CPG model with a learning method is proposed for achieving adaptive limbless locomotion. The key issue of the framework is to find a mapping that converts external stimuli to proper sensory input, so as to modify the output of the CPG model and thus enable the limbless robot to adapt to environments. A genetic algorithm (GA) based method is applied to the framework. Through a slope climbing experiment, it is verified that the GA-based method can achieve adaptive limbless locomotion.

From the results of simulations and experiments, the hierarchical control architecture is confirmed to be a solid platform for improving the locomotive behaviors of limbless robots.

Contents

List of Figures

List of Tables

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 undulation. Beside sidewinding, snakes can perform lateral undulation, concertina locomotion and rectilinear locomotion and their combinations to adapt to environmental changes [4].

Another example is caterpillar locomotion. Different from snake locomotion that using pure body undulation, caterpillars utilize prolegs to grip the substrate and pull the legs forward sequentially to form locomotion [5]. 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 [6].

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 [7]. 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 [8]:

- 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 limbless locomotion is produced and adapted to environmental changes? In fact, animals' morphological and physiological behaviors dominate their locomotion patterns [9]. 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 [10]. 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 [11]:

- **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 enables the robotic system a robustness to the extent 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.

- **Exploration**: Robots have the benefit of being able to explore many hazardous areas a human could not reach, such as deep sea areas and the planets in space [12]. For exploration tasks, there is no prior knowledge about the environment. A robot may get stuck, fall over, and even get damaged resulting in loss of mobility. To avoid such situations, the robot must be good at terrain traversing. Limbless robots satisfy this requirement. As highlighted in the last section, a limbless robot with redundant design can distribute body mass over a large area to support itself. Furthermore, its low center of gravity can prevent it from falling over. NASA has developed such a limbless robot for space exploration. The robot may help explore other planets and perform construction tasks in space.

- **Inspection**: In many cases, it is necessary for humans to inspect environments that are either too small or too dangerous for them. For instance, a human may need to detect the blockage of pipe networks, or to inspect a reactor in a nuclear plant. The inspection tasks usually take place in unstructured and tight environments. To accomplish inspection tasks, robots are required to be flexible and sensitive. Limbless robots carrying onboard sensors are considered to be very suitable for such tasks. On the one hand, the benefits of a small cross section enables the robot to climb through narrow and tight environment easily. On the other hand, the onboard sensors can help the robot to collect environmental information and carry out efficient inspection and accurate localization.

- **Search and rescue**: A search and rescue task requires rescuers to find trapped survivors in a collapsed structure after earthquakes or other disasters. Survivors may be buried amongst the debris that both human rescuers and trained dogs usually fail to find, much less to approach. Additionally, searching in partially-collapsed buildings is a dangerous task for rescuers due to potential risk from further collapse. Limbless robots would be a valuable aid to rescuers [13]. As mentioned earlier, a limbless robot has redundant design and a small cross-sectional area which allow it to penetrate deep into the rubble. The limbless robot can be outfitted with a variety of sensors, such as cameras, microphones and infrared detectors so as to obtain infomation in the rubble. Sensing information can be sent back to rescuers in real time to help locating survivors. This would make the search and rescue task in the rubble faster and more effective.

- **Medical treatment**: Limbless robots could be potential medical devices for aiding in surgical procedures. The robots can help to overcome the limitations of traditional surgeries. For example, instead of opening large sections of skin and tissue during the surgery, a limbless robot with small cross section allows surgeons to operate with far less damage to the body. The robot could crawl into interior tissues along the small incision and make further diagnosis using onboard sensors. This would dramatically reduce the patients' suffering and healing time. Furthermore, with the help of limbless robots, surgeries will become faster and easier, resulting in reduction of medical costs.

- **Reconnaissance**: Limbless robots could also be applied to military reconnaissance. Because of their small size and moving low on the ground, a limbless robot is not easy to find, especially when it is disguised with protective color. Moreover, by means of the diversity of limbless motion, the robot is able to move surreptitiously into hostile areas and further use onboard sensors for reconnaissance. Israel has developed such a reconnaissance robot with a camera and microphone installed in its head and plans to apply it for combat missions.

Not only morphological imitation, but also internal imitation such as locomotion generation is essential to limbless robots. This is the core of biomimicry, which transfers the knowledge from biological findings to engineering applications. Although the underlying mechanism of the CPG circuits in the spinal cord of animals has not been fully understood yet, there is an increasing interest in applying CPG models to the field of bio-inspired robot for locomotion control. A lot of interesting biologically inspired robots have been developed, such as humanoid robots [14, 15], quadruped robots [16, 17], snake-like robots [18, 19, 20, 21] and fish-like robots [22, 23, 24, 25]. As a bio-inspired alternative to other algorithm-based control systems such as finite state machines, CPG-based methods have been increasingly used for locomotion control in robots with multiple joints, especially for online rhythmic trajectory generation [26]. Many appealing properties including distributed control, the ability to deal with redundancies, fast control loops and allowing the modulation of locomotion by simple

control signals make CPG models suitable for different modes of locomotion motion. Furthermore, the combination of CPG with other control methods results in a higher locomotion adaptability. For instance, Arena et al. used a multi-template approach to construct appropriate cellular neural networks to achieve a VLSI chip CPG controller [27]. Based on the Ekeberg's CPG model of lampreys, evolutionary algorithms was adopted to evolve the CPG's neural parameters and connection weights for improving locomotion performance [28, 29]. Crespi and jspeert utilized CPGs and a gradient-free algorithm to optimize swimming and crawling gaits online [30].

Even though in the literature attempts have been made to apply CPG models to bio-inspired robots including limbless robots, there are no clues and criteria about how complexity of a CPG model should be, how the model can be extended to interact with environment via sensory feedback, and what the gaps are to combine the model with other intelligent control methods. On the one hand, there exists a certain complexity in original biological CPG models. It is unrealistic to directly apply these models to control the robots. For this reason, it is necessary to reduce model complexity while maintaining most properties of the model such as neuromodulation and sensory feedback integration. On the other hand, the robotic implementation provides a suitable platform that allows for much more control of locomotion patterns and exploration of parameter space by means of experimental analysis. Hypothesis of new types of CPG models or modification on CPG models applied to such a platform thus can be thoroughly evaluated, which provides sufficient flexibility for understanding how animals move.

1.3 Scope & goals

In this book, we concentrate on the locomotion control of limbless robots. Even though limbless locomotion patterns have been investigated and implemented by some researchers using kinematic models or sinusoidal function based methods [11, 31, 32], CPG models are rarely employed on limbless robots for 3D locomotion. Considering the biological features of CPG models, it would be more convenient to generate and modulate limbless gaits in a CPG-based control architecture. It is also possible to integrate some biological mechanisms such as the reflex mechanism into the control architecture to realize fast reflex response. Furthermore, since CPG models usually offer a good substrate for learning and optimization algorithms, they are suited to be applied to a control architecture in a hierarchical manner. In this way, a CPG model served as the foundation of the control architecture would facilitate the design of the higher-level control.

A limbless robot with a modular configuration is considered as our test bed. A modular approach has many advantages for designing a multi-functional mobile robot. It enables robots to reconfigure, which is essential for tasks that are difficult for a fixed-shape robot. It also makes a mobile robotic system versatile, robust, cost-effective and fast to prototype, so that different robots can be reconfigured fast and easily for the testing, exploration and analysis of new ideas.

Taking the considerations aforementioned, we present in this book how to design and implement a hybrid control hierarchy including the reflex level, CPGs with biological features and a higher intelligence level to considerably improve the locomotive behaviors of limbless robots. The robot is supposed to (i) have a re-configurable design that is suitable for different types of exploration tasks; (ii) have full locomotion capabilities in a 3D environment, and (iii) be able to interact with the environment based on perceptual

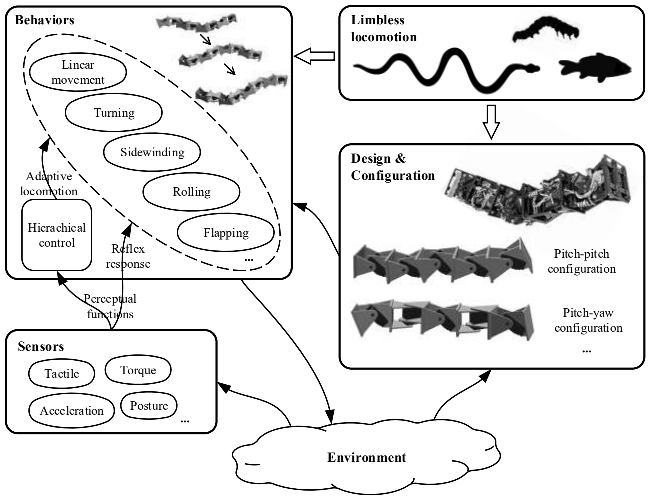

Figure 1.1: The fully functional integration of the limbless robots.

functions. More precisely, the robot should be not only capable of generating various limbless gaits, but also able to react in a sophisticated way to environmental stimuli with the help of multiple sensors.

Figure 1.1 illustrates the functional integration of our modular limbless robot. First, limbless animals from nature inspire the design of limbless robots, targeting ease of configuration and rapid prototyping. We cannot design versatile limbless robots to deal with all types of environments. Instead, we can reconfigure the robot if the environment changes, e.g., from crossing a corridor to climbing over a slope. Second, limbless locomotion patterns in nature will help guide the development of limbless gaits. Here, CPG models are considered a feasible solution in implementing limbless behaviors. We will look into the model design in Chapter 4 and the gait implementation in Chapter 5. Third, proper onboard sensors, either interoceptive or exteroceptive, or both, allow the limbless robot to perceive the environment. With the help of perceptual functions, a closed loop control will be the main concern. How to realize hierarchical control, with a lower-level for reflex response and a higher-level for adaptive locomotion will be introduce in Chapter 6 and Chapter 7, respectively.

2

Overview of Limbless Robots

Limbless robots have become a hot topic in the last few decades. Despite their significant advantages and potential applications as described in Chapter 1, there are always unexpected challenges when developing a limbless robot, such as lack of propulsion, unstable gaits, and poor payload capacity. Rational design and efficient control are of great importance to the success of limbless robots. In this chapter, we present the state of the art of the limbless robots, explore their propulsion types, and introduce feasible control methods.

2.1 State of the art

A growing number of research groups has become actively involved in limbless robot research. Here, we cannot list all developed limbless robots in the world, but those that are famous and have significance in design and control of limbless robot.

2.1.1 Active cord mechanism

As one of the pioneers in this field, Hirose started the study of snake-like robots in the early 1970s [19]. He first developed a snake robot called the Active Cord Mechanism (ACM) that could perform lateral undulation. The purpose of his work was to understand the mechanism of locomotion in real snakes. Latter, he developed a series of snake-like robots that followed from this work. The functionality of the robots has been promoted from 2D motion to 3D motion. Recently, he and his colleagues developed an amphibious snake robot that can move as easily on the ground as in water. Figure 2.1 shows the features of different prototypes in Hirose's lab developed from the beginning to the present.

The first one is the ACM III, which has a length of 2 meters and a weight of 28 kg. The robot is made up of 20 joints with a yaw-yaw connection. Since each joint consisting of a servo system can only bend to the left and right, the robot is constrained to 2D motion. Hirose used this configuration to study the serpentine gait. To generate the forward propulsion for the serpentine gait, he installed small wheels on the bottom of each joint along the direction of the body. The idea is to make it easy for the robot to slide in the tangential direction and difficult to slide in the normal direction. As a result, the ACM III achieved serpentine movement at a speed of approximately 40 cm/s [33].

The ACM Revision 1 (ACM-R1) was built in 1995. [34] redesigned the robot with 16 smaller modules and utilized wireless communication to control it. The robot can move with a velocity of about 50 cm/s, which becomes faster than the ACM III. Furthermore, it has higher mobility with serpentine locomotion as due to a skate blade placed under each joint, the robot succeeded to glide on ice in a skating rink [35].