A Review of Central Pattern Generator-Based Approaches for Quadruped Robot Locomotion

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This paper reviews locomotion control approaches for quadruped robots, with a specific focus on methods based on Central Pattern Generators (CPGs). CPGs are bio-inspired neural circuits that generate rhythmic motor commands, offering a computationally efficient solution for controlling complex robotic movements. The study explores fundamental concepts of quadruped locomotion, including gait types and parameters and details the application of CPGs, highlighting the use of different oscillators, such as Hopf and Van der Pol, and their integration with Inverse Kinematics. The review emphasizes the potential of hybrid control techniques, which combine CPGs with learning-based methods to enhance the robot's adaptability and robustness on various terrains. The paper concludes that CPGs, especially when combined with hybrid control strategies, present a promising and efficient solution for achieving stable and adaptive locomotion in quadruped robots.
Keywords: Quadruped Robot. Locomotion Control. Bioinspired Control. Central Pattern Generator.
Abbreviations: CPG, Central Pattern Generator. RL, Reinforcement Learning. ZMP, Zero Moment Point. MPC, Model Predictive Control. WBC, Whole-Body Control. VMC, Virtual Model Control. SLIP, Spring-Loaded Inverted Pendulum.

Quadruped robotics has gained increasing prominence due to its versatility in various applications, such as inspections in confined and hard-to-reach places, exploration of uneven terrain, and activities that require climbing [1-3].

This versatility is mainly due to the articulated structure of its legs, which gives it versatile mobility to ensure stability, optimizing locomotion in different environments [1,4].

Several methods for controlling the locomotion of quadrupedal robots have emerged over the past few years, whether model-based or learning-based methods. Among them, the Central Pattern Generator (CPG) is an approach that combines utility and convenience since it can control the robot's locomotion using little computational power [5].

This paper aims to explore the main concepts related to quadruped robot locomotion, with an emphasis on control techniques based on Central Pattern Generators and their applications. The methodology for this review involved a systematic

search of scientific databases, including IEEE Xplore, Scopus, and Google Scholar. The search was conducted using keywords such as "quadruped robot," "locomotion control," "Central Pattern Generator," and "bio-inspired control."

The selection criteria prioritized review articles and research papers with robust simulation or experimental results, with a focus on publications from the last decade to ensure the inclusion of state-of-the-art techniques. We also present the fundamental concepts of quadruped locomotion, from the concepts of gait to a brief presentation of other control techniques used, and the Central Pattern Generators as a technique for controlling the locomotion of quadruped robots, presenting the different oscillators used and different applications. Nevertheless, we finally present final considerations on the use of CPGs for the purpose of quadruped robot locomotion.

Quadruped Robots Locomotion

The locomotion of a quadruped robot can be defined as a coordinated set of movements of its four legs, giving the robot the ability to move around the environment [6]. This coordinated movement of the quadruped's legs is defined by external parameters and a specific type of gait,

which will determine the sequence and contact time of each leg with the ground. The type of gait adopted directly impacts the robot's performance, influencing not only its stability, but also its agility and speed of locomotion [4].

Characteristics of Gait in Quadrupedal Robots

Usually, the gait cycle is divided into two subsequent phases: the support phase, in which the foot is in contact with the ground, propelling the robot in the direction of movement, and the swing phase, in which the foot is executing a trajectory in the air until the next point of support [7].

The type of gait adopted will define when each leg will be in the stance or swing phase. In static gaits, such as walking and crawling, the robot always keeps at least three legs in contact with the ground, which ensures greater stability at the expense of slower movement [1]. On the other hand, dynamic gaits, such as trot, pace, and gallop, have phases in which only one or two legs are in contact with the ground, enabling higher speeds of locomotion and requiring more sophisticated control to maintain balance and stability.

The robot's locomotion speed can be calculated according to the gait parameters, such that the speed v is given by:

$$v = \beta \frac{d_{step}}{T} \qquad (1)$$

Where T is the period of a complete cycle of the foot movement, given by the sum of the stance phase period (T_{st}) and the swing phase period (T_{sw}), $T = T_{st} + T_{sw}$ [8], β represents the duty cycle of gait, that is, the ratio between the support time and the total cycle time, $\beta = T_{st}/T$ (values greater than 0.5 suggest greater stability), and finally dstep represents the step width. In addition to these parameters, the maximum elevation of the foot during the swing phase, or ground clearance (g_c), and the maximum penetration into the ground during the stance phase, or ground penetration (g_p), are other important parameters that influence the robot's ability to overcome obstacles [8].

Locomotion Control Methods

In order for the quadruped to be able to follow a certain gait while maintaining body balance, control methods must be applied to ensure precise movements and stability [1,4]. Such methodologies are categorized as model-based control (whether bio-inspired or not) and learning-based control [4].

Among the model-based methods, Model Predictive Control (MPC) stands out, which anticipates and optimizes actions considering constraints and plant reaction forces [4], and Whole-Body Control (WBC) [9], which determines ideal torques to minimize tracking errors. The Zero Moment Point (ZMP) criterion [10] is widely used to ensure stability by keeping the center of mass projection within the support polygon formed by the feet in contact with the ground. There are also approaches that explore analogies to physical or biological systems for generating movements, such as Virtual Model Control (VMC) [11] and the Spring-Loaded Inverted Pendulum (SLIP) model [12].

Learning-based controllers enable the robot to develop control policies through environmental interaction. Reinforcement learning (RL), a prominent approach, enables the robot to learn to maximize cumulative rewards using algorithms such as Proximal Policy Optimization (PPO) and Soft Actor-Critic (SAC) in continuous and high- dimensional environments [4]. The main advantage of RL lies in its adaptive learning capability, allowing it to generalize to complex and unseen terrains via Domain Randomization, as well as offering resilience to disturbances and optimizing energy efficiency [4,13,14].

A summary and comparison of these control methods are presented in Table 1.

Central Pattern Generators for Quadruped Robotics

Central Pattern Generators, in biology and neuroscience, represent a set of neuronal cells present in the spinal cord of vertebrates, responsible for generating rhythmic motor movements [5].

Table 1. Comparison of different locomotion control methods for quadruped robots, highlighting their main advantages, disadvantages, and notable applications.

Control Methods	Main Advantages	Main Disadvantages	References
Pure CPG (Hopf, VDP)	Computational simplicity, natural motion generation.	Open-loop, low adaptability to unexpected terrain	[15,16]
CPG + Inverse Kinematics	Precise foot position control, facilitates obstacles avoidance	Higher complexity can generate unfeasible joint solutions	[8,18]
Hybrid CPG (with RL)	High adaptabilidy and robustness, learns to handle different terrains and speeds.	Requires trainning (often time-consuming), can exhibit unexpected ("black-box") behavior	[8,20-23]
Model Predictive Control (MPC)	Optimizes future trajectory, good for dynamic and aggressive locomotion.	High computational cost	[4]
Whole-Body Control (WBC)	Controls the entire ronot's body, considering all forces and torques.	Complex model, difficult to implement	[9]

Unlike the other control methods presented, using CPGs it is possible to directly control the joints of the quadruped [15], or even control each of its legs [8] in a synchronized manner without the need for complex trajectory planners, state machines, or optimizers.

Oscillators for CPG

The application of CPGs to quadruped robotics represents a bioinspired control technique that consists of mathematically representing the rhythmic signals generated by CPGs through oscillatory, nonlinear, and coupled dynamic systems, which allow the generation of rhythmic movement control signals even when the control and sensory systems are isolated [1].

Although all oscillators usually share the same structure, the phase shift and coupling between them allow the creation of varied locomotion patterns, or different types of gait [5] (Figure 1).

The Hopf oscillator, represented by Equation 2, is one of the most widely used due to its mathematical simplicity and maturity [15]:

Where x and y represent the state variables. The term $r^2 = x^2 + y^2$ represents the squared radial

Figure 1. Coupling diagram of the four CPG oscillators used to generate the trot gait. The double-ended arrows indicate the mutual phase influence between each leg's CPG.
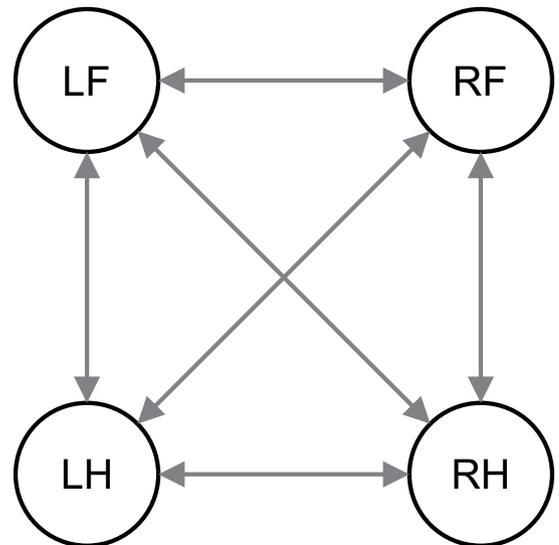
$$\begin{cases} \dot{x} = \alpha(\mu - r^2)x - \omega y \\ \dot{y} = \alpha(\mu - r^2)y + \omega x \\ r^2 = x^2 + y^2 \end{cases} \quad (2)$$

distance from the origin in the phase plane, directly related to the instantaneous amplitude of the oscillation. The parameter μ is a positive constant that defines the desired squared amplitude for a stable limit cycle. The dynamics of the oscillator, governed by the term $\alpha(\mu - r^2)$, continuously drive the system's amplitude r towards $\sqrt{\mu}$. The constant α influences the convergence speed to this limit cycle (stabilization), and ω defines the natural frequency of the oscillation. The frequency ω can be modified to generate asymmetric locomotion signals, so that the frequency of the stance phase (ω_{st}) is different from the swing phase (ω_{sw}), according to Equation 3, allowing the adoption of different gaits [1].

$$\omega = \frac{\omega_{st}}{e^{-ay}+1} + \frac{\omega_{sw}}{e^{ay}+1} \qquad (3)$$

Another promising approach to gait control is based on the Van der Pol oscillator, a model that also relies on limit cycle theory for the generation of periodic and stable oscillation signals [16]. One of the main characteristics of this oscillator is its ability to converge to a single limit cycle, regardless of the initial conditions, resulting in a periodic and stable motion trajectory. The mathematical equation of the Van der Pol oscillator is given by Equation 4.

$$\ddot{x} - \alpha(p^2 - x^2)\dot{x} + \omega^2 x = 0 \qquad (4)$$

Where the term $\alpha(p^2 - x^2)\dot{x}$ acts as a nonlinear damping, where α influences the shape of the output signal, p determines its amplitude, and ω defines the natural oscillation frequency. By adjusting the coupling topology and phase shift between multiple Van der Pol oscillators, it is possible to modulate the different phases of the robot's legs, allowing it to change its gait in a fluid and adaptable manner [16].

There is also the amplitude-controlled phase oscillator, presented by Ijspeert and colleagues [17], represented by Equations 5 and 6, where θ and r are the state variables, representing the phase and amplitude of the oscillator, respectively, while ω and μ represent its intrinsic frequency

and amplitude, with a being a positive constant that interferes with the stabilization speed of the oscillator.

$$\ddot{r} = a\left(\frac{a}{4}(\mu - r) - \dot{r}\right) \qquad (5)$$

$$\dot{\theta} = \omega \qquad (6)$$

Applications of CPG in Quadruped Robots

Due to their simplicity and ability to generate natural movements, CPGs have been widely used to control the locomotion of quadrupedal robots. While some CPG applications in quadrupedal robots consist of using the signals generated by the CPG directly to control the robot's joints [14-16], another possibility is to use the CPG in combination with Inverse Kinematics [8], in which four coupled oscillators are used, one for each leg of the quadruped, so that the signals generated by each of these are converted into positions for the robot's legs, and subsequently converted into angular positions for the joints through the calculation of Inverse Kinematics [18] (Figure 2).

Due to the fact that, in essence, CPG is an open-loop control, strategies such as the one proposed in Righetti and Ijspeert [19] seek to close this loop to make the robot more adaptive. In this specific work, the loop is closed by changing the stance and swing phases of the legs only when the leg actually touches or leaves the ground, avoiding transitions at the wrong times that can destabilize the robot, especially on uneven terrain.

Another very efficient way to close the control loop and give the robot greater responsiveness and adaptability is by using hybrid control techniques. In recent years, CPG applications in combination with Reinforcement Learning have stood out, as they allow a trained agent to adapt to different conditions. Several studies focus on training an agent to parameterize CPG oscillators to ensure stable locomotion that is adaptable to different speed commands [8]. A similar study is proposed in [20], in which the CPG is kept fixed, while the agent learns corrections to the joint positions

Figure 2. Comparison of two hierarchical CPG control architectures: (a) the direct mapping approach, and (b) the inverse kinematics approach with a low-level PD feedback controller.

(a)   (b)
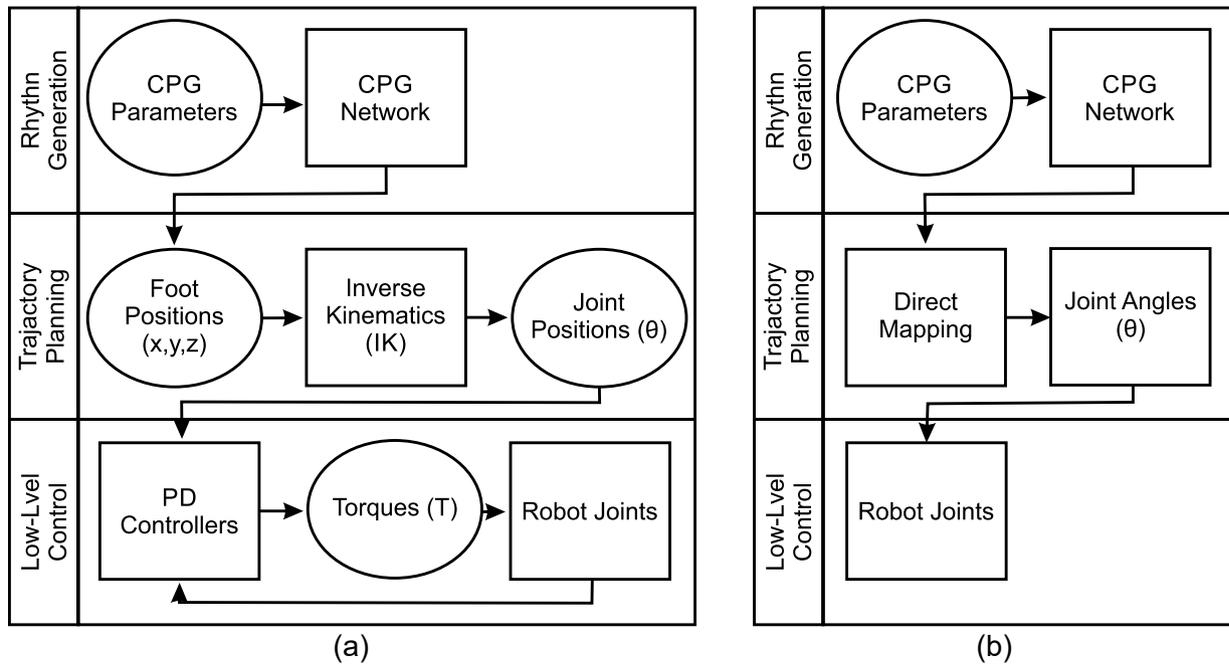
calculated by the CPG in conjunction with Inverse Kinematics, giving the robot greater adaptability and stability.

In addition, there are applications that explore the use of Reinforcement Learning to enable smooth transitions between different types of gait [21] or even to cross gaps in the ground [22] and navigate autonomously by using exteroceptive data [23].

Conclusion

This paper presented the main concepts of quadruped robot locomotion, with an emphasis on control methods based on Central Pattern Generators and their applications.

The use of CPGs in quadruped robotics represents a simple and efficient way to control this type of robot, enabling the adoption of different types of gaits by simply changing the coupling or difference between the oscillators, without the need for trajectory planners or optimizers. In addition, CPGs require low computational power for their application, not necessarily requiring a sensing system integrated with the control system to be implemented.

Hybrid control methods stand out, combining CPG techniques with learning-based methods, providing the robot with the ability to dynamically adapt to the environment and different terrains.

In future work, Central Pattern Generators will be applied to a real quadruped robot [17] to analyze their effectiveness in locomotion control.

Acknowledgement

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