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Analysis of the CPG-DRL framework for Quadruped Robot Locomotion

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Abstract—**Autonomous robots are expected to be crucial in mitigating the lack of precise border surveillance in complex terrains, especially within forests, mountains, and industrial settings, focused on predicting the entry of terrorists and illegal refugees. These robots must demonstrate navigational proficiency in both controlled areas, such as border control gates and borders with plane surfaces, and unplanned country borders in daily surveillance tasks, including mountains, forests, and mud. In this regard, quadruped robots are attracting considerable interest due to their ability to carry substantial surveillance equipment while navigating inclines and obstacles. Given the environment-dependent characteristics of optimal gait patterns, it becomes a necessity for mechanisms capable of independently and effectively optimizing gait patterns for adaptation to different scenarios. To address these challenges, we explored a model for quadruped locomotion that combines central pattern generators (CPGs) with deep reinforcement learning (DRL). Using both external and internal sensing, the agent learns to coordinate rhythmic movement among multiple oscillators to follow speed instructions, while also adjusting these instructions to avoid bumping into things around it. This research helps to use DRL to study important questions in neurology, such as how certain pathways, connections between oscillators, and sensory information affect walking patterns. Moreover, this paper will present fundamental knowledge, research trends, and challenges regarding the implementation of the CPG-DRL framework in robotic perception.**

Keywords—**Central Pattern Generator (CPG); Gait, Locomotion; Quadruped; Deep Reinforcement Learning (DRL)**

I. INTRODUCTION

NATURAL and border settings are generally highly complex, marked by uneven landscapes and unorganized obstacles in dynamic spaces. Humans and animals rely on their strong limbs to navigate intricate terrain by walking, climbing, running, and adjusting their body positions. This frequently requires immediate visual perception and spatial awareness of the environment to maneuver limbs and circumvent obstructions. In reality, both humans and animals possess a restricted field of vision, although our limbs can extend significantly beyond our visual perception limits. When limbs extend beyond the visual field or in settings where visual perception is compromised (for instance, in darkness or around dense landscapes), the ability to perceive obstacles to perception through orientation perception becomes essential. Robots have generated significant curiosity over the last decade due to their ability to navigate challenging and intricate environments, including space, perform search and rescue operations, and execute tasks independently of human interaction [1]. Developing a control system for robots capable of navigating and moving through complex 3D landscapes while adeptly circumventing barriers without dependence on external sensor data, including vision or lidar systems, poses a considerable challenge [2]. Figure 1 provides an exemplary illustration of quadruped locomotion on different types of terrain.

Fig. 1: Illustration of quadruped locomotion in different terrains, including walking on flat terrain, stair terrain, and uneven terrain, respectively.

In real scenarios, animals use their tactile sense to perceive the presence of barriers in their vicinity. Robots refer to this process as obstacle detection. However, touch sensors in robotics are generally positioned solely in designated areas (for instance, the bottoms of the legs or fingers), leading to a significant portion of the robot's anatomy being incapable of immediately detecting obstacles. Consequently, the implementation of collision detection for each limb is of paramount importance. Using collision avoidance, robots can identify unfamiliar barriers and direct their limb actions, allowing navigation through restricted terrain or finding their way in darkness. Facilitating robots' ability to accurately identify and react to obstacles not only improves their autonomy but also ensures safety during interactions and operations in uncertain situations. Different landing spots form the four-legged robot's trajectory. In rough terrain, legged robots demonstrate better

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locomotion capabilities than conventional wheeled or tracked robots, allowing them to achieve goals in increasingly complex environments [3].

Animals perform complicated navigational tasks on a variety of terrains to seek food or avoid hunters. To effectively plan and implement agile actions in unfamiliar contexts, exteroceptive perception is essential for both control and planning functions. Incorporating exteroception for both animals and robots presents a chance (expectation, organizing) as well as a difficulty (more multidimensional measures, noise) for control systems. On the other hand, animals quickly gather complex sensory information and have built-in systems that share control between the spinal cord and the higher areas of the brain, including the motor cortex. This questions the idea that all movement commands come from higher control areas (like the biological version of modern optimal control methods and learning techniques). This paper examines the combination of CPG with DRL for improved biological analogies. The CPG is shown as a group of oscillators, with its conditions changed by feedback from external sensors (like visual information) and internal sensors (like speed and touch feedback) to create strong navigation rules. Robots have made significant progress in understanding and imitating animal locomotion. Successful uses include controls inspired by biology, such as CPGs [4]–[6], model-predictive control [7]–[9], and learning-based methods [10], [11]. However, despite these improvements, we still don't fully understand how animals learn to move and how their brain and spinal cord work together to control that movement. The agility of robotics has not yet reached that of animals. This study draws inspiration from various domains to analyze the legged movement of a quadruped robot by integrating biologically inspired oscillatory models with artificial intelligence capabilities.

A recent breakthrough includes the integration of DRL and CPG, resulting in the creation of the CPG-RL methodology, which improves the algorithm in reinforcement learning. This integrated method uses DRL to enhance the CPG parameters, enabling the CPG architecture to adapt to more complex environments. This work examines quadruped locomotion through the integration of CPG and DRL, using DRL to continuously modify CPG variables, providing stable rhythmic motions with the resilience inherent in learning-based control. The CPG-DRL system allows for quick transfer from simulations to real-life use without needing to change the setup, which reduces the need for adjustments and fine-tuning when applying strategies to real quadruped robots. The analysis shows that the framework can help maintain a steady walk and trot on uneven ground and while carrying heavy loads, effectively avoiding disturbances in real-world situations. The research looks at how the system uses a small observation area (like where the feet touch and the CPG phases) while still being understandable, allowing users to easily change walking features like body height and leg spacing in real-time without needing extra training. It highlights that CPG-DRL creates natural and adaptable walking patterns that correspond to biological locomotion patterns, unlike traditional DRL methods, making it easier to study and adjust for different walking tasks.

This study is motivated by the growing interest in reinforcement learning-based locomotion controllers and their ability to improve the mobility and adaptability of quadruped robots. As researchers investigate innovative approaches and architectures, it is essential to synthesize existing information and identify interesting avenues for future research. This study seeks to provide a thorough understanding of the fundamental principles, approaches, and advancements in the sector, empowering both academics and professionals to improve current work and investigate new approaches.

The remaining article is divided into four sections: Section II consists of the most recent work surveys related to this study, Section III provides background information on CPG and DRL, Section IV presents a discussion on some recent CPG-DRL framework research outcomes, Section V discusses the challenges and future research prospects, and Section VI provides the concluding remarks.

II. LITERATURE SURVEY

The CPG technique was developed long ago, but is still very useful and important whenever it is incorporated into the DRL for locomotion of quadruped robots. Quadruped robot locomotion guidance has been thoroughly examined using diverse strategies, including bio-inspired, model-based, and learning-based techniques. The simultaneous use of these strategies is progressively acknowledged as an effective strategy for improving locomotor performance. Recently, many researchers have focused on an integrated system that has CPG and DRL for planning robot paths.

Bellegarda *et al.* [12] propose a methodology to incorporate CPGs, specifically platforms with linked oscillators, within the DRL architecture to achieve resilient and omnidirectional quadrupedal locomotion. The agent learns to directly change the natural settings of the oscillators (how strong and how fast they move) and coordinate the rhythmic movements of different oscillators. This method allows the use of DRL to explore questions related to neuroscience, such as how pathways, connections between oscillators, and sensory information contribute to walking patterns. The suggested method was practiced in a simulation and then successfully applied to the Unitree A1 quadruped, showing strong performance even when faced with new challenges, especially when carrying an additional weight of 13.75 kg, which is 115% of what a typical quadruped weighs. The technique was tested using different observation areas based on body position sensing, showing that the suggested framework can work without the need for random changes in the environment and with very little feedback. Alongside the oscillator states, it is feasible to include solely contact booleans in the space of observation.

Bellegarda *et al.* [13] propose an approach that allows visually guided quadruped mobility by incorporating exteroceptive perception and CPGs, which are frameworks for interconnected oscillators, within the DRL paradigm. Leveraging both exteroceptive and proprioceptive sensing, the agent acquires the ability to synchronize rhythmic activity across several oscillators to follow velocity directives, while simultaneously overriding them to prevent collisions with the surroundings.

This approach examined some unresolved inquiries in robotics and neurological research: 1) What could be the function of specific interoscillator couplings among oscillators and might such couplings enhance a sim-to-real transition for navigation resilience? 2) What are the effects of using a system that remembers information compared to one that doesn't, in terms of being resilient, saving energy, and tracking results for navigation tasks from simulation to real life? 3) How do animals endure significant sensory latencies while still performing natural and strong gaits? Smart movement strategies are developed in a simulation to solve these issues and successfully adapt to the Unitree Go1 quadruped, allowing it to navigate well in different environments. The results from this approach show that the CPG, certain connections between oscillators, and memory-based strategies greatly improve energy efficiency, stability against disruptions, and 90-ms sensory delays, as well as tracking performance for better real-world navigation.

Watanabe *et al.* [5] propose a data-driven DRL method to optimize a structure-based control strategy that includes CPG. This method, called hierarchical reinforcement learning with the central pattern generator (HRL-CPG), is then evaluated to see how it could be used in real robotic control systems. Steady gait patterns were achieved after a relatively limited number of trials and errors. Consequently, it can be inferred that the suggested HRL-CPG technique might be useful for a viable DRL technique, allowing dynamic structures, including actual or realistic robots, to adjust to diverse surroundings within a reasonable temporal timeframe.

Deshpande *et al.* [14] create new DeepCPG policies that include CPGs as part of a larger neural network, allowing for a thorough understanding of movement behaviors in a DRL setup. This method demonstrates its usefulness on physical engine-based insectoid robots. DeepCPG policies help learn effective movement strategies quickly in complex sensory environments (like those involving vision), doing better than current methods. An analysis is conducted on the DeepCPG policies utilizing a modular robot setup and multiagent DRL. The results show that gradually adding complexity with these rules in a modular way could greatly improve how sensors and motors work together in a robot. The findings demonstrate the effectiveness of deriving more complex autonomous systems from basic ones grounded in biological principles. The experimental results provide evidence for an insectoid robot platform in which DeepCPG originally learned rules using a simulation system and subsequently transferred them to practical robots without further fine-tuning.

Seto *et al.* [15] presents a posture response network that interfaces smoothly with the CPG network to improve stable walking on uneven surfaces. This enhancement is attained only by sequentially progressive learning with a streamlined reward function. The suggested method enhances the utility of CPG-based movement in unplanned settings and advances bio-inspired control techniques for quadrupedal movement. The suggested method incrementally enhances CPG-based locomotion on an irregular landscape by acquiring CPG metrics and foot positioning modifications in relation to pre-established trajectories through a two-stage learning approach.

Xu *et al.* [16] proposes the integration of CPG and DRL to attain steady mobility in quadrupedal robots. By configuring various features of the CPG, this method produces an archive of diverse joint paths. Through DRL, the locomotion skills for a quadruped robot can be modified for various movement patterns produced by distinct sets of CPG variables. The simulation's experimental findings demonstrate that the suggested technique can sustain consistent forward mobility on level terrain as it executes diverse motion patterns, and it has strong exploration characteristics in unorganized areas. The proposed technique achieves steady locomotion in the desired direction using a CPG-RL approach, which may be challenging if one relies solely on CPG signals to control the joints of quadruped robots.

Zhang *et al.* [17] presents a model-free RL system utilizing CPG for fault-tolerant control (FT-CPG). The system uses a method inspired by nature to create walking patterns and trains in parts to handle different problems that can happen at the same time in multiple joints. FT-CPG employs a fault-tolerant CPG module to produce secure gaits, simultaneously leveraging neural network-based policies to detect errors and synchronize the rhythmic actions of the CPG, thereby maintaining the capacity to follow velocity directives in fault scenarios. Experiments demonstrate that FT-CPG exhibits resilience in unforeseen circumstances, when a single leg endures failures across several joints, with every joint arbitrarily facing locked or powerless malfunctions. Moreover, the suggested framework maintains the robot's omnidirectional movement. In the end, the zero-shot sim-to-real transition worked well on the actual Unitree Go1 robot, helping to reduce problems with multiple joints in the legs.

Shafiee *et al.* [18] propose that viability, including the prevention of falls, constitutes a significant requirement for gait changes. This approach examines the onset of gait transitions via the interplay between supraspinal drive, the spinal cord's CPG, the physical body, and exteroceptive perception, utilizing DRL and robot methodologies. In accordance with findings from quadruped animals, this approach demonstrates that the shift from walking to trotting in quadruped robots on level ground enhances both durability and power conservation. Additionally, the impact of discontinuous topography (i.e., traversing sequential gaps) on inducing gait transitions is examined, revealing the formation of a trot-pronk transition for avoiding ineffective situations. The only improvement after changing gaits on both smooth and uneven surfaces is viability, which shows that making these changes is mainly about being practical, while other benefits are just extra results of being viable. Furthermore, this investigation exhibits cutting-edge agility for quadrupled robots in demanding situations.

III. BACKGROUND INFORMATION

Investigations of animals and robotics indicate that the power saving, stability, and avoidance of peak forces (damage) to muscles and joints are credible reasons for the transition between various gaits in animals. This article examines the possible significance of an additional criterion: an understanding of viability, which formalizes the idea of preventing a fall during legged mobility. Viable states are those states from which a system may prevent deterioration through appropriate action choices [19]. Viability is an important main goal for controlling movement, influenced by factors such as regular patterns, steady walking (in a Lyapunov context), and unexpected events such as falling into holes or hitting obstacles. Although viability pertains to regularity and gait stability, it encompasses a more extensive idea. We used a layered system inspired by biology, along with robotics and DRL techniques [20], to study how quadrupeds change their walking patterns.

A. *Central Pattern Generator*

Many DRL methods need outside phase input, but there is a growing need to create phases internally to avoid needing these inputs, using Central Pattern Generators (CPGs) for this purpose. Animals can modify their locomotor gait patterns based on traveling velocity and terrain conditions. Research has focused on exploring the mechanisms of animal locomotion, with research indicating that legged movement is inherently rhythmic due to the presence of specialized neurons known as CPG inside the spinal cord of animals. CPGs are a network of interconnected oscillatory neurons that can generate rhythmic signals autonomously, independently of external sensory input. The rhythmic signals generated by CPGs are essential for actions that require periodic motions, such as breathing, running, walking, swimming, and flying [21]. CPGs are attracting attention in the robotics domain due to their oscillatory and rhythmic characteristics. Researchers have created many different CPG systems with various levels of complexity to study how biological central pattern generators create rhythms, including detailed biological models, connectionist frameworks, and simpler mathematical models [22], [23].

Using CPGs is helpful for artificial systems because it helps them move more steadily and resist vibrations by syncing to simpler, low-dimensional patterns. The way animals move is designed so that spinal CPGs create basic rhythmic movements, while higher brain areas, such as the motor cortex, brain cortex, and spinal cord, adjust these movements based on the environment. Rybak *et al.* [24] have proposed that biological central pattern generators (CPG) generally have a two-level system, which includes a half-center rhythm generator (RG) that controls how fast movements occur and pattern formation circuits that determine the specific ways muscles are activated. Comparable groups are also used in robotics, as evidenced in references [12] and [25]. References [20] and [12] describe the controller that we use.

1) Rhythm Generator (RG) Layer: We use amplitude-controlled phase oscillators to mimic the CPG circuits of the RG layer for the spinal cord, which can change the output signal by adjusting various decision factors, as in (1) and (2) [26]:

$$\dot{\phi}_i = \omega_i + \sum_j A_j W_{ij} sin(\phi_j - \phi_i - \varphi_{ij}) \tag{1}$$

$$\ddot{a}_i = \beta(\frac{\beta}{4}(\mu_i - a_i) - \dot{a}_i) \tag{2}$$

Where

- a_i = The oscillator amplitude.
- ϕ_i = The oscillator phase.
- μ_i = The intrinsic amplitude.
- ω_i = The frequency.
- β = The convergence factor, which is a positive constant.
- The couplings between oscillators are denoted by the phase biases φ_{ij} and the weights W_{ij}.

2) Pattern Formation (PF) Layer: To move from the RG states to the joining instructions, we first figure out the positions of the foot and then calculate where the joints need to be using inverse kinematics. This procedure delineates the Pattern Formation (PF) layer, with the appropriate foot positional coordinates established as follows in (3) and (4) [18].

$$Y_{i,foot} = Y_{off,i} - L_{step}(a_i)cos(\phi_i) \tag{3}$$

$$X_{i,\text{foot}} = \begin{cases} H + L_{\text{clr}} \sin(\phi_i), & \text{if } \sin(\phi_i) > 0, \\ H + L_{\text{ptr}} \sin(\phi_i), & \text{otherwise.} \end{cases} \tag{4}$$

Where

- L_{step} = Step length.
- L_{clr} = The maximum ground clearance for swing.
- L_{ptr} = The maximum penetration into the ground for stance.
- Y_{off} = A set point that moves the oscillation equilibrium towards Y direction.
- Adjusting the horizontal offset of the foot Y_off signifies guided spinal regulation of the overall position of the limb, avoiding the rhythm generation layer.

B. *Deep Reinforcement Learning*

Reinforcement learning (RL) offers robots a framework and methodologies to cultivate complex and demanding behaviors. The challenges presented by robotic issues provide impetus, impact, and rationale for progress in reinforcement learning. A significant range of obstacles in robotics might be fundamentally expressed as RL difficulties. RL enables a robot to autonomously discern optimal behavior through trial-and-error engagement with its environment [27]. When employing the DRL approach for autonomous navigation, the objective is to identify the optimum course of action to guide a quadruped robot to its destination through interaction with its environment.

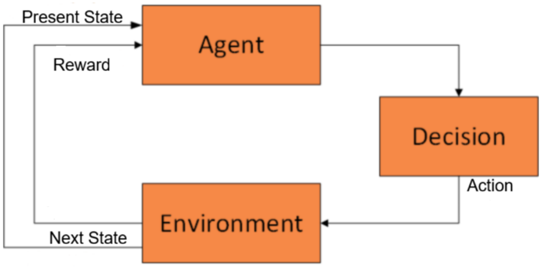

Fig. 2: DRL agent interactions with the environment.

The traditional navigation system can be integrated with or replaced by DRL-based navigation. Due to the trial-and-error learning mechanism of reinforcement learning, it is prohibited for legged robots to collide with nearby obstacles during the actual training period. Before deployment in a legged robot that enables navigation and real-time decision-making, the deep neural network (DNN) is frequently trained in a simulated environment. Figure 2 provides an illustration of the interactions of DRL agents with the environment and the decision-making process.

DRL is a machine learning algorithm that enables a learning agent to generate optimal decisions. The agent performs an action in the observed state, subsequently observes another state, and receives the corresponding reward. The aim of DRL is to determine the optimal decision-making agent, or policy, that optimizes the projected total of rewards in a particular state. Despite its demonstrated effectiveness as a comprehensive control technique, DRL faces significant challenges. It needs the direct acquisition of effective policies from the environment and self-states, involving precise parameter optimization, intricate formulation of reward functions, and comprehensive data gathering. The robot and CPG are considered continuous-time differential dynamical systems, specifically (5) and (6) [5]; they are shown as discrete-time difference dynamical systems to make things clearer. The state change is characterized by the subsequent probability.

$$\frac{ds_r}{dt} = f_r(s_r, c_r), \tag{5}$$

Where

- s_r = Robot state signal. s_r comprises physical attributes such as pose and position.
- c_r = Robot control signal.

$$\frac{ds_p}{dt} = f_p(s_p, c_p), \tag{6}$$

Where

- c_p = The feedback signal is utilized to modify the phase of the oscillator within the CPG.
- s_p = The phase of the robot state.

IV. DISCUSSION OF DIFFERENT APPROACHES

In hierarchical RL, the use of a CPG is used to facilitate locomotion of a quadruped robot simulator on various terrains [5]. This paper introduces a data-based DRL method for improving policies that include CPGs and evaluates how well it works in real situations, expecting it to be useful for real robotic control systems. Quadruped robots frequently exhibit a rhythmic and cyclical movement pattern. CPGs, which can create rhythmic signals, are often used to control robots that mimic biological movement because they work similarly to the way real animals move. However, attaining stable locomotion in the intended direction might be difficult when exclusively depending on Central Pattern Generator inputs to regulate joints in quadrupedal robots. This study integrates CPG with DRL to achieve stable mobility in quadruped robots using [18]. The hierarchical learning architecture for the controller of a quadruped robot facilitates steady locomotion, inspired by the periodic motion generation mechanisms observed in mammals. The framework is termed hierarchical reinforcement learning with a central pattern generator (HRL-CPG) due to its hierarchical RL structure for the coupled dynamic system, which incorporates a pattern oscillation network— a specific type of CPG [5]. By simply integrating a CPG network with the RL-based controller, as depicted in Figure 3 (a), the policy transforms into a dynamic stochastic policy as shown in (7) [5].

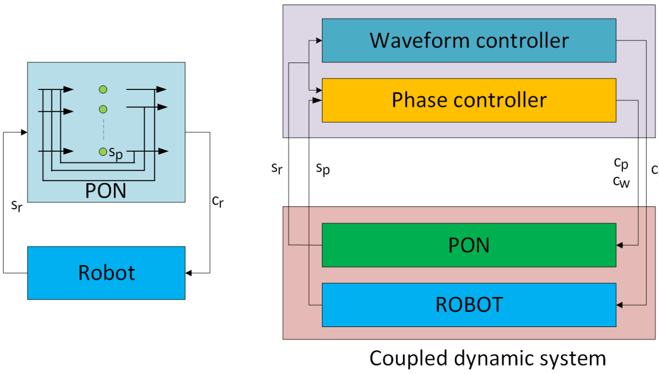

Fig. 3: Schematic representations of the CPG-based control system based on [5]. (a) The control framework for the robot utilizes a phase oscillator network (PON). (b) Control framework for the interconnected dynamic systems application of a feed-forward neural network.

$$\pi_r(c_r|s_r) \sim p(c_r|s_p), \tag{7}$$

To tackle this non-Markovian characteristic, the PON is segmented into two components: the inner state and the input. The former is seen as an element of the control target along with the robot, forming a coupled dynamical system. The RL is employed to improve the performance of the integrated system, which consists of controllable physical components and the CPG network, as seen in Figure 3(b). The studies indicate that the proposed method attains superior sampling effectiveness in adaptation in relation to Deep Transition, a leading state-of-the-art technique. With respect to the suggested approach, which learns variants of a singular gait, Deep Transition investigates several gait patterns, generating diverse adaptive features.

Combining CPGs with DRL gives planned and effective way to manage quadrupedal mobility. When we use rhythmic motion patterns with CPGs, it's often easier to learn how to move than when we use DRL methods that try to control movements directly. The CPG part helps the robot walk in a steady and smooth way, and the DRL policy changes important things like strength, speed, and timing to fit different tasks and environments. The explanation of duties makes learning more stable, makes samples less complicated, and makes them more robust. A primary advantage of the CPG-DRL paradigm is its improved generality and effectiveness in transferring simulations to real-world applications. The CPG enforces biologically inspired gait patterns, leading to a learned policy that is less likely to exploit simulation artifacts. Furthermore, reduced action space promotes faster policy convergence and improves interpretability; hence, it streamlines debugging and gait modification. Domain randomization during training improves robustness in assessing variability in robotic dynamics and terrain features. An approach to hierarchical locomotion control in modular quadrupedal robots using CPG-DRL is presented in [28].

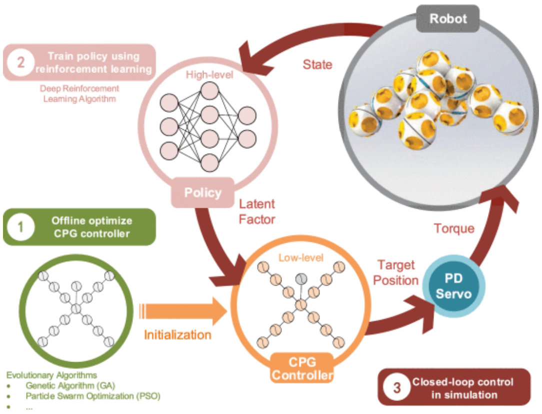

Fig. 4: Hierarchical learning structure designed around a two-level CPG and the modular quadrupedal robotic cell robot [28].

The hierarchical architecture technique is described in Figure 4 as follows: A model of a CPG-based controller is built based on the shape of the quadruped and adjusted beforehand to create the necessary shared space path for steady walking patterns (Figure 4, step 1). The proportional-derivative (PD) control might track such paths by immediately outputting torques at every joint. Subsequently, a higher-level policy network is trained using reinforcement learning within the simulation (Figure 4, phase 2). Ultimately, the acquired policy adjusts the CPG settings, allowing the quadruped to comply with user orders (Figure 4, step 3).

V. CHALLENGES AND FUTURE RESEARCH TRENDS

Artificial intelligence technology has significantly improved the way quadruped robots move, adapt to their surroundings, and make decisions, thanks to better algorithms and teamwork in different fields. The improvement of reinforcement learning algorithms has reduced the limitations of traditional methods, making it easier to create effective walking patterns and apply them in different situations [29]. Bionic methods equip quadruped robots with natural locomotion and lifetime learning attributes similar to those of biological entities [30]. Multi-modal perception integration and adaptive navigation systems have created a closed loop from regional control to global autonomy.

Despite progress, quadruped robots continue to face significant obstacles while implementing on rough terrain. The challenge of implementing real-world simulations is crucial because it makes it very hard for quadruped robots to move from research settings to the commercial marketplace and military applications. This issue significantly obstructs the efficient integration of educational research findings into real-world contexts [31]. The issue of computational efficiency is imminent. The existing low computational efficiency hinders robots from fulfilling the rigorous demands of actual applications requiring swift response and decision-making, including in industrial surveillance and disaster recovery. It also restricts the continued investigation and use of intricate algorithms and models in scholarly research.

Quadruped robots have been studied for military and security uses, including surveillance and handling hazardous materials [32]. Their ability to navigate difficult terrains and transport specialized sensors might enhance situational awareness in dangerous environments. There are many basic problems that need to be closely looked at to make quadruped robots. Finding the best way for a robot to navigate a wide range of terrains, including rocky slopes and obstacles of various shapes and sizes, is difficult. It needs algorithms that can find strong paths through complicated places, which will generally not be easy for wheeled robots. Another problem is how to use power wisely. The robot needs to have an appropriate ratio between reliable control and movement systems. This means that you need to look closely at strong power storage options and reliable actuators [33]. Maintaining a unique and secure human-robot interaction remains a challenge, requiring a profound interest in robotics, psychology, and knowledge of human factors. However, the system has some limits. If the robot only moves in certain ways, it might not be able to move in other ways as well, and those limitations could make it harder for it to do things like jump quickly or in an unexpected way. Also, if the CPG configuration or interactions aren't set up right, it can be harder to gain knowledge of the best ways to move. Future research might look at flexible central pattern generator designs, layered strategies, or mixed methods that combine CPG-based movement with learning systems tailored for specific tasks [34].

The CPG-DRL system is a good choice for animal robots that need to move around in the real world because it combines model-based control with data-driven learning. A four-legged robot can go to places that no one else has been to, such as forests, hills, rivers, and deserts, while keeping an eye on the border. It could use its legged agility to get around things and stay safe where normal vehicles cannot. This integration ensures prompt handling of military surveillance risks, making it a reliable method of monitoring the border area. Incorporating AI techniques allows the robot to progressively improve its vulnerability recognition and categorization precision, according to changing security problems [35]. Armed with sensors including RGB and thermal cameras, LiDAR, radars, and electromagnetic sensors, it might track activities both day and night, identify and categorize humans or automobiles through embedded AI, generate immediate alerts, and communicate information to a control center. It operates in independent, autonomous, or integrated multi-robot systems to enhance visibility, mitigate risk to humans, and offer constant, adaptive surveillance in challenging frontier areas. Thus, the CPG-DRL framework can also play a vital role in border surveillance through the military induction of quadruped robots.

VI. CONCLUSION

Quadruped robots are playing a vital role in different fields of applications, including military, firefighting, underwater search operations, and many more. The proposed study analyzed the role of the CPG-DRL framework in the navigation of quadruped robots. This paper shows how CPG is crucial for the gait transitions of the legged robot. This paper provides background information on the CPG-DRL technique that can make quadruped robots more robust to implement in complex scenarios. Furthermore, we have validated the theoretical concepts with a comparative discussion of two recent research outcomes. This article comprehensively discusses future research trends and challenges in the field of legged robots. This article can provide excellent information for early-stage researchers.

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