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TOPICAL REVIEW

Intelligent Control of Multilegged Robot Smooth Motion: A Review

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ABSTRACT Motion control is crucial for multilegged robot locomotion and task completion. This study aims to address the fundamental challenges of inadequate foot tracking and weak leg compliance control in multilegged robot motions. The first section summarizes and discusses the feasibility and operability of smooth motion for multilegged robots based on the necessary conditions and application value of walking over complicated and unstructured terrain. The second to fourth sections present a qualitative research method of literature review to study the effects of several factors on the smooth motion of multilegged robots, including foot force perception and motion planning, active compliance control, gait stability, and Deep Reinforcement Learning (DRL) control. We conducted a case analysis of multilegged robots using traditional Nonlinear Model Predictive Control (NMPC), biomimetic Central Pattern Generator (CPG), and DRL control in the latest international open-source projects to help readers further follow the latest open-source algorithms for legged robot motion control. In addition, we analyze the challenges these influencing factors face in optimization and provide suggestions for effectively promoting the realization of review objectives. In the fifth section, we discuss the challenges of springy gait and intelligent switching control in solving the problems of poor foot tracking and weak leg compliance. We explore and forecast the potential application of the Probability Density Function (PDF) control of the foot force in the smooth motion of multilegged robots. In the sixth section, we systematically discuss, analyze, and summarize the existing problems in this research field. We also highlight the shortcomings of existing research methods, look forward to future research areas, and highlight the obstacles that need to be overcome to promote future research in this field.

INDEX TERMS Multilegged robot, foot planning, gait stability, compliant control, probability density function control, deep reinforcement learning control.

I. INTRODUCTION

The current state of robotic research demonstrates multi-technology integration, functional redundancy, and failure tolerance in response to various application scenarios. Different research topics in the professional realm have unique emphases. Control theory experts specialize in control optimization strategies, whereas robotic research encompasses collaboration, integration, intelligence, and autonomous fine work with varying degrees of autonomy. The fundamental issues and research hotspots for multilegged robots include intelligent force-position control and dynamic balancing control, which are critical for their adaptability to rugged terrains and impediments.

Multilegged robots have become a research focus because they aim to navigate multi-mountain environments with large slopes, large-scale gullies, ground contact mechanics, and road damage from natural disasters or earthquakes. The

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multilegged walking robot's steady and flexible motion, discontinuous support, and unique landing sites allow it to replace conventional wheeled and tracked ground mobile robots for activities on complicated terrain. Additionally, it is adaptable to unknown, unstructured, and rough terrain, making it a valuable asset for various applications [1], [2]. Consequently, researchers in this field have focused on practical applications of multilegged robots. Based on the number of feet, multilegged robots are classified into single-footed, bipedal, tripodal, quadripedal, and hexapod. Multilegged robots provide numerous benefits such as superior stability, remarkable load-bearing capacity, and exceptional adaptability to different terrains, which make them ideal for use in complex environments with varying degrees of stiffness.

Multilegged robots are susceptible to sensor noise and installation errors. In foot-ground interaction, dynamic collision is a vibrating and discontinuous contact issue. Multilegged robot control is hampered by internal force conflict, foot-ground slip, unpredictable foot force distribution, and gait variability. The unpredictability of terrain and body motion control approaches are also a subject of study for multilegged walking robots in the field. Controlling a probabilistic robot's compliant gait can enhance uncertainty controllability [3].

Next, from the perspective of intelligent control, the purpose of the overview, and the structure of the entire article, we further clarify the context and function of the Introduction section. Regarding intelligent control methods, we classified the importance of different strategies that can improve the movement of multilegged robots from the perspectives of traditional, reinforcement learning, and Probability Density Function (PDF) control. This section summarizes and discusses the feasibility and operability of multilegged robot smooth motion, starting from the necessary conditions and application value of walking on complex and unstructured terrains. In addition, we analyzed and discussed the smooth motion control of multilegged robots in terms of depth and breadth, popularity, and persistence of this research direction, highlighting the importance and popularity of research on smooth motion control.

Multilegged robots face challenges when traversing uneven terrains, damaged road surfaces, or cracked pavements. The You Only Look Once (YOLO) series of visual models can be utilized for surface detection under unfavorable conditions [4]. When integrated with neural networks, YOLO visual methods can accomplish 3D spatial target detection and motion path planning for robotic arms [5]. Although these research advancements are beneficial for the ongoing development of legged robots, this study focused on multilegged robot system control. Therefore, the following section scrutinizes the implementation of system control methods that enable the smooth movement of multilegged robots. Hadi et al. introduced an innovative hardware and firmware design for an intelligent optical force-torque sensor using a Field-Programmable Gate Array (FPGA). Furthermore, this development kit enables sensor utilization and integration in the development of a Robot Operating System (ROS) [6]. Although the use of ROS for robot control is prevalent in robotics [7], [8], [9], given the emphasis of this study on the control algorithm for multilegged smooth movement, the subsequent section concentrates on system control algorithms instead of operating system research. Shi et al. proposed a control strategy that precisely utilizes bifunctional sensors to control pneumatic systems [10]. The application of this strategy has the potential to improve the control precision of joint drive systems in multilegged robots. The mathematical model of a multilegged robot is not universal, and it is impossible to describe all multilegged robots using a unified mathematical model. Simultaneously, the model of a multi-joint manipulator cannot fully generalize the model of a multilegged robot. Therefore, the core objective of this study is to investigate how to control the motion of a multilegged robot system, particularly in the case of known or unknown models. In other words, this study aimed to explore how to design a motion control strategy for a multilegged robot system to achieve effective motion control.

A. INTELLIGENT CONTROL IN MULTILEGGED ROBOT SMOOTH MOTION

1) TRADITIONAL INTELLIGENT CONTROL

A multilegged robot can exhibit an extensive Range of Motion (ROM) with conventional intelligent control. Wei et al. proposed a strategy for mapping the Central Pattern Generator (CPG) output to the joint drive Angle [11]. However, the proposed CPG algorithm does not provide a feedback system. Therefore, quadrupedal robots do not exhibit good slope movement or overtaking performance. Qiao developed a conductive polyurethane hydrogel with long tensile and electrical conductivities [12]. It can be applied as a flexible strain sensor to detect robot joints and footsteps. Shang et al.designed the trajectory of the active impact motion of a moving gait using a CPG network based on a Hopf oscillator. In addition, the robot can modify its stride immediately after the target object moves to avoid falling [13]. We can learn from this method and apply it to tasks with active impact motion. Xu et al. proposed an Adaptive Variable Impedance Control (AVIC) scheme to adjust the target stiffness and maintain a horizontal attitude on unknown terrain [14]. On this basis, the motion planning of wheel-legged robots can be further improved by recognizing unknown terrain and integrating an environment perception system that can enhance the motion adaptability of a robot in an unknown environment. Kwon et al. proposed a flexible and effective Model Predictive Control (MPC) system for unipeds, bipeds, and quadrupeds [15]. This method can generate a wide range of motions at an interactive rate, including walking and running on sloping variable terrain, jumping over hurdles, implicit quadruped gait conversion, adapting to lunar gravity, and responding to external forces.

Although traditional algorithms can achieve the desired motion control effect, they cannot self-update or automatically correct the motion ability of multilegged robots during landing applications. Therefore, with the rapid development of artificial intelligence, multilegged robots are being utilized in new opportunities to navigate complex and unstructured terrain.

2) REINFORCEMENT LEARNING INTELLIGENT CONTROL

Underperformance, energy limits, and online learning of legged robots still require improvement. Reinforcement Learning (RL) techniques such as random gradient and deep reinforcement have been investigated for bipeds, quadrupeds, and hexapods. These computationally intensive technologies are challenging to deploy in edge-computing systems. These technologies can be more efficient regarding energy consumption and throughput, because they rely on complex sensors and data preparation.

In the Spiking Neural Networks (SNN) framework, Lele et al. examinPed a legged robot with a synchronous gait generated by a CPG [16]. This method combines the effectiveness of an SNN with the synchronous motion of a CPG-based system, resulting in a significant performance boost in the end-to-end learning of mobile robots. Yang et al. presented a security reinforcement learning system that alternated between a security recovery strategy to prevent the robot from entering an unsafe condition and a learner approach optimized to accomplish the task [17]. This strategy achieved fewer than five drops in 115 min of hardware time when it was applied to real-world quadrupedal robots. Although this strategy yielded satisfactory findings, we did not consider the model uncertainty caused by environmental and nonlinear dynamics in the theoretical analysis, which should be improved to increase the generalizability of the method. Yu and Rosendo proposed a multimode motion framework called automatic residual reinforcement learning that aims to provide a quadrupedal robot with the ability to walk on both legs [18]. Future studies will include the following applications of robots with multimodal motion frames.

a. The robot could stand up and navigate obstacles in biped mode to adapt to different terrains.
b. It can use the forelimb as a manipulator in biped mode.
c. A forelimb can be used to press buttons to improve the performance of a robot in a human-centered environment.

3) PROBABILITY DENSITY FUNCTION INTELLIGENT CONTROL

Probabilistic multilegged robots working in the field must always handle ground movements caused by solid earthquakes, wind, waves, and significant road stiffness spans. In addition, random excitations, such as animal group fluctuations and vibrations in aircraft and vehicle engines, frequently affect robots. In the last 20 years, researchers have extended the theory of the randomly distributed control of non-Gaussian systems. They used a non-Gaussian random distribution modeling and control method to examine the output PDF shape [19], [20], [21]. This method uses the PDF output as the control object. In this paper, for the first time, we suggest using the shape of the PDF of the output force to control how random noise affects the force-position flexibility of the gait [22].

Using a simple continuous variable dynamic or discrete variable system to analyze and control an actual system is difficult for a probabilistic robot walking on a road with many obstacles. However, hybrid systems, such as switched-networked control systems, substation switching control, robot walking control, and aero-engine control, can be used to analyze and control actual systems. Intelligent switching control improves multilegged springy gait [23].

Overall, multilegged robots with high stability and weight capacity can serve as additional tools to reduce the risk of combatants and as highly effective equipment for future battles. Researchers can improve the mobility of multilegged robots by studying human and animal adaptations. Compliant motion research has enhanced the adaptability of multi-terrain robots. This theory is advantageous for a robot walking on non-flat ground and in various environments, ensuring smooth landings and minimal foot-to-ground impact. This theory advances bionic gait compliance control research and provides a theoretical basis and technical guidance for designing and controlling robotic gait switching systems.

The multilegged robot has poor foot force tracking and leg compliance control capabilities, especially foot force-position hybrid control. This paper summarizes the human perception and motion planning of a walking machine, active compliance control of a robot-compliant gait, intelligent switching control, and intelligent learning control with a reasonable prediction of the ground force PDF [24], [25]. This study focused on the smooth motion of multilegged robots, including motion planning, leg compliance control, motion stability, foot force PDF control, and intelligent switching control of gait [26], [27].

B. PURPOSE OF THE STUDY

The continuous application of intelligent control technology inevitably has varying effects on multilegged robots. This study evaluates the effects of different control strategies on multilegged robots regarding smooth motion, learning, and compliance control. We aim to determine whether intelligent control enhances the effectiveness and efficiency of multilegged robot task execution, ultimately improving the motion stability and compliance efficiency. This research will benefit all stakeholders in the multilegged robotics industry by contributing to the ever-growing knowledge, theory, and empirical discovery of how intelligent control affects multilegged robots. It will also promote evidence-based decision-making and leadership practices for multilegged robot mechanisms among scholars, professionals, and policymakers. Furthermore, this study aimed to examine the effect of intelligent control on the smoothness of motion in multilegged robots and evaluate its precise nature, including enhancing their motion capability and learning efficiency. Researchers can develop strategies and measures in cooperation with multilegged robot mechanisms to promote the beneficial impact of intelligent control on the flexible motion of multilegged robots.

In the introduction, we present the feasibility and operability of achieving smooth motion in multilegged robots. We then classified the smooth motion control of multilegged robots in the second to fourth parts, covering motion planning and foot force perception, active compliance control, stability, and reinforcement learning, which are the three main aspects affecting smooth motion. The overall structure of this paper is as follows:

1) In the first part, we summarize and discuss the feasibility and operability of achieving smooth motion in multilegged robots by walking on complex and unstructured terrains. We also analyze and discuss the smooth motion control of multilegged robots from the perspectives of depth and breadth, popularity, and persistence of this research direction, highlighting the importance and relevance of research on the smooth motion control of multilegged robots.
2) In the second part, we discuss the research status of motion planning and force sensing integrated into robot systems in detail, and provide suggestions to solve the problems in the current main achievements in this direction.
3) In the third section, we analyze the active compliance control strategy for quadrupedal robots, including its advantages and disadvantages. We compared and discussed these methods with similar techniques, critically evaluated the relevant conclusions, and provided suggestions for improvement.
4) In the fourth section, we review the gait stability theory of quadrupedal robots and the application of reinforcement learning. We highlight the limitations of this study and the challenges related to its application.
5) In the fifth section, we propose a flexible robot gait based on PDF intelligent learning and switching control to solve the free-gait fluency of multilegged robots in an unstructured walking environment.
6) In the sixth section, we systematically discuss, summarize, and prospect the entire text based on a full-text review and exploration, to provide readers with a better understanding of future work.

II. MOTION PLANNING AND FORCE PERCEPTION OF WALKING ROBOT

The multilegged robot's smooth locomotion on complex, nonstructural terrain (refer to Fig. 1) results from interdisciplinary integration. The primary focus of our study was the gait and foot trajectory planning for a multilegged walking robot. The gait planning approach was used to separate the swing and support phases, corresponding to the motion sequence of the robot legs. After calculating gait, we planned the trajectory of each foot. The sensory system of the robot plays a critical input role with force perception serving as the foundation of the foot force sensory system. There are four standard methods of force perception: joint current, single-axis force sensors, pressure-type electronic skin, and six-dimensional force sensors.

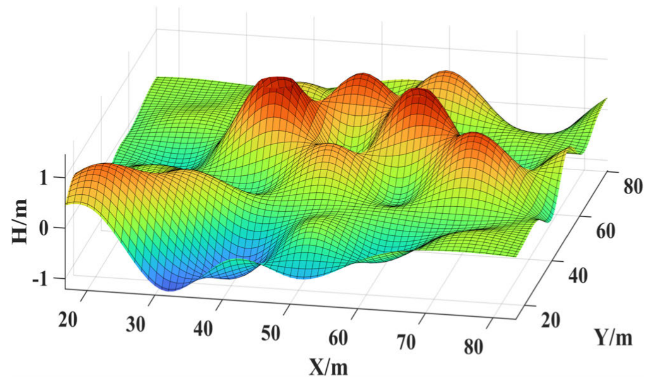

FIGURE 1. Simple unstructured ground.

The recorded foot force is often integrated with a robot system for motion planning and control, such as foot trajectory and gait planning, for contact force perception of the robot foot. Subsequently, individual research histories and advancements are elaborated in greater detail.

A. GAIT PLANNING OF WALKING ROBOT

Gait planning is a control method that enables a walking robot to move based on a predetermined gait pattern. The gait of a walking robot can be classified as regular or irregular (free gait), with examples of regular gaits including biped diagonal, tripod, and quadruped gaits. Experimental results have shown that animals exhibit rhythmic walking on flat terrain and free walking on rugged terrain [28].

The bionic gait of a multilegged robot is often used in migration application research. Pearson and Franklin analyzed typical insect locusts walking on different topographies and found that locusts did not use a specific but irregular gait [29]. This result illuminates locust walking on rugged terrain and provides a theoretical foundation for bionic robot gait research. Researchers have proposed numerous gait planning strategies for irregular gaits, including local rules, CPG, intelligent learning algorithms, and model-based methods. Cruse compared a hexapod robot's walking ability to an insect robot. A gait generation method based on local rules was proposed based on a study of the coupling mechanism between the insect legs. This method improves the movement ability of a walking robot based on the interaction between terrain [30], [31]. Chen et al. presented an environmentally adaptive bionic gait with a phase factor of 0.25 and an occupation coefficient of 0.454 by studying the crab walking gait. This method simulates the natural gait of a robot encountering environmental and foot-related constraints. This strategy results in a more robust gait. The foot trajectory of this gait automatically adjusts to terrain deformation, as demonstrated by comparing it with a quadruped gait at the same pace [32].

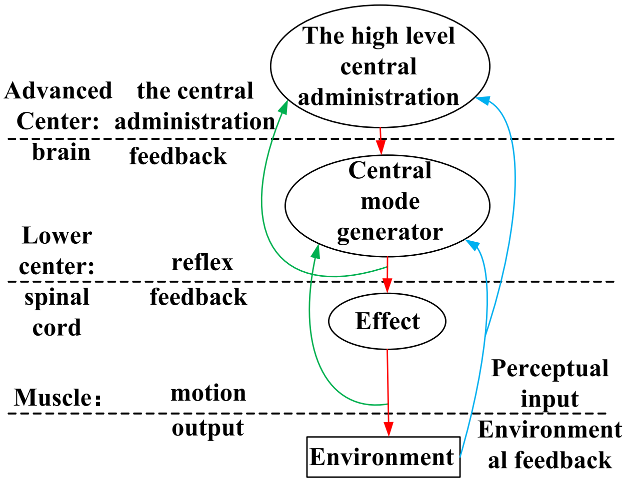

FIGURE 2. Biorhythm motion control system.

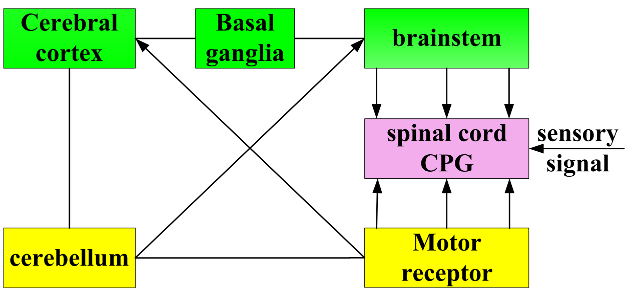

FIGURE 3. CPG control movement principle.

1) WALKING ROBOT AND CPG CONTROL

a: CPG CONTROL

Fig. 2 depicts the complex rhythmic motion control system found in higher animals. This system is comprised of four key components: a high-level center, a central mode generator, an effector, and an environmental feedback system. This highly sophisticated system enables smooth and coordinated motion in higher animals.

Biologists believe that the central pattern generator in the spinal cord or thoracoabdominal ganglion regulates rhythmic behavior in animals. As shown in Fig. 2, the forward channel uses the CPG as the central control unit, forms a rhythmic control signal, and controls the effector to complete a motion task. The primary function of the central nervous system is to send motor commands that initiate and regulate rhythmic movements by integrating the central feedback signal from the central pattern generator, sensory signals from the animal's body, and other signals.

The motion principle of the CPG control is shown in Fig. 3. The cerebral cortex generates motor consciousness, and the basal ganglia emit an inhibitory tension signal to select the motion mode. After the inhibitory signal activates the brainstem motor center, it is transmitted through the reticular spinal cord bundle to the spinal cord CPG. The CPG of the spinal cord interacts with the perceptual feedback to produce

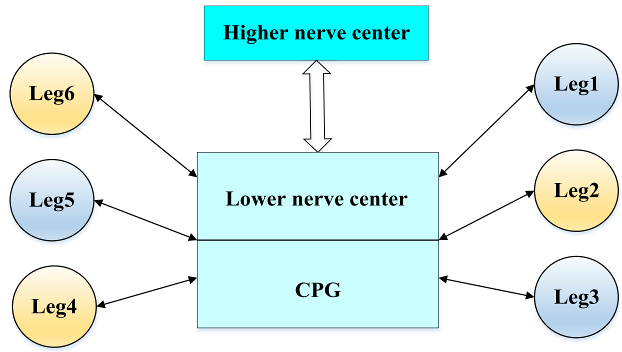

FIGURE 4. Schematic diagram of the six-legged robot CPG.

rhythmically stable movements. Efficient coordination and monitoring of animal motor activity are achieved by the cerebellum's integration of sensory and motor signals with central commands, meeting the rigorous standards of top-tier publications.

As shown in Fig.3, the CPG is the central control unit of rhythmic motion. In the CPG, synaptic connections between neurons are plastic; therefore, they present mixed output signals that allow the animals to complete various movements. The gait planning method based on the CPG principle considers each foot of the robot as a neuron. With this method, the robot walked by periodically triggering the motion of each foot. Fig. 4 illustrates its principle, and Table 1 compares the gait of various walks [33]. A CPG is a network that can generate rhythm outputs without sensor feedback. They are typically combined with intelligent algorithms to build different CPG networks and generate a more adaptive gait. Wei et al. proposed a gait planning method based on a central pattern generator and the Back Propagation Neural Network (BPNN) [34] to realize stable gait planning of quadruped robots and improve motion performance. Liu et al. proposed the Multilayer CPG (ML-CPG) model based on a semi-central CPG model. This method solves the problem of the traditional simplified single-layer central mode generator model, which lacks satisfactory performance in engineering applications in which robots face unknown environments and access feedback [35]. Inspired by CPG, Liu et al. proposed a bionic method. The CPG network comprises six CPG units based on Matsuoka's neural oscillators, which are used to generate oscillation signals [36]. The hexapod robot achieved steady walking on rugged terrain by using the CPG network's output phase signal to generate the end-effector trajectory signal for each of the six legs, calculating joint angles through inverse kinematics, and adjusting motion parameters based on feedback data.

The Hopf-type harmonic oscillator has fewer parameters than Matsuoka neural oscillators, and each parameter has a distinct effect on the oscillator's performance. Adjusting the output signal's amplitude, frequency, and phase was simple. Consequently, Hopf oscillators are frequently used as oscillation units in CPG networks. This section discusses the

TABLE 1. Comparison of multilegged gait.

Common hexapod gait	(bionic) principle and method
triangle gait	The robot walks using sets of three legs: foot 1, foot 3, and foot 5 form one set, while the remaining three feet form another set, forming a triangular supporting structure. As the three legs in one set push backward, the other set lifts forward to take over support.
quadrangular gait	Four legs are typically in the supporting phase for the three gait types. Legs 1 and 4, legs 2 and 5, and legs 3 and 6 are grouped into three or differently into two sets. As the robot moves, each set of legs is raised and swung in turn. This gait is known as quadrupedal gait.
Pentagonal gait	In the case of a six-step cycle, the lifting order changes more than three kinds of gait, which can be Leg1-Leg6-Leg2-Leg5-Leg3-Leg4 or Leg1-Leg4-Leg2-Leg6-Leg3-Leg5. Different walking methods make the support surface of the robot change in different ways in the whole motion cycle to meet different requirements of overcoming obstacles or climbing.

mathematical model corresponding to the motion parameters of a multilegged robot, as shown in Eq. (1).

$$\begin{cases} \dfrac{dx}{dt} = \alpha\left(\mu - r^2\right)x - \omega y \\ \dfrac{dy}{dt} = \beta\left(\mu - r^2\right)y + \omega x \\ r^2 = x^2 + y^2 \\ \omega = \dfrac{\omega_{st}}{e^{-by}+1} + \dfrac{\omega_{sw}}{e^{by}+1} \\ \omega_{st} = \dfrac{1-\beta}{\beta}\omega_{sw} \end{cases} \tag{1}$$

where x and y are the oscillator state variables, that is, the oscillator's output. The α convergence speed coefficient regulates the limit of the loop convergence speed. The square of the oscillator amplitude is μ. Because CPG is commonly implemented on robots with support and oscillation phases at frequency x and y, respectively, the CPG model includes two constants: occupation factor β and b parameters. b specifies the frequency of the transitions between ω_{st} and ω_{sw}, where ω is the oscillator's frequency. Eq. (1) shows the typical use of CPG in multilegged robots. The following section addresses the application of CPG in conjunction with intelligent control for multilegged robots.

Walking robots have many applications in military, rescue, medical, and other fields. CPGs are typically used to control walking robots. Nevertheless, CPG control of a walking robot presents various challenges. Incorporating more sensors, machine learning methods, and comprehensive task-planning processes can improve robotic controls' robustness, accuracy, and universality. Future research directions include intelligent robot control and multi-robot cooperative tasks.

b: THE COMBINATION OF INTELLIGENT ALGORITHMS AND ROBOT

Applying a traditional CPG model to the control of modern robots is challenging. Hence, combining CPG with other intelligent control algorithms and learning algorithms is a research hotspot for solving the problem of parameter adjustment.

Li et al. proposed an artificial bee colony (ABC) learning algorithm for CPG gait generation to achieve an optimal gait pattern for a humanoid robot [37]. He et al. proposed a new biped real-time walking generation method based on the Zero-Moment-Point (CPG-ZMP) hybrid control algorithm [38]. This technique can improve the CPG parameter robustness and biped robot walking stability. Tutsoy used a Maple multibody analysis template and Modelica custom component template to obtain the inverse kinematics solution of a robot leg combined with a CPG-based Reinforcement Learning (RL) algorithm [39]. The value function is maximized, whereas the time difference error is reduced to zero. The RL algorithm improved the CPG settings to provide an effective walking pattern. Multilegged robots, such as hexapod and quadruped robots, can move steadily in a target direction and area [40].

After reviewing the literature on multilegged robot movement planning, it is evident that there are three typical approaches: path-formulation rules, bionic motion rhythms, and fusion neural network algorithms. Using simple rules to simulate creature locomotion is often the most cost-effective and time-efficient method to design a known and straightforward environment. In this study, the robot's movement was based on the bionic principle of the CPG motion algorithm. Although this algorithm helps realize movement rhythm, it cannot learn in an unstructured environment, making it less practical than a position-rule design. However, robots with intelligent control algorithms can learn and predict during walking, which makes them more suitable for complex field environments. Combining the CPG algorithm with intelligent control allows varying movement flexibilities, depending on the selected algorithm.

Regarding model degradation, these design approaches have advantages owing to the simplification of the robot model.

2) THE MODEL-BASED GAIT PLANNING METHOD

In addition, the model-based gait planning method simplifies a complex robot system into a relatively simple model

TABLE 2. Classification of gait planning methods.

Gait planning method	The main idea
Based on local rules	The researchers established simple rules to simulate the creature's gait based on the interaction between the foot and its environment and the constraint relationship between the foot and its foot.
CPG (central pattern generator)	From the perspective of imitating animal gait rhythm control, each foot of the robot is regarded as a neuron. The robot can walk by periodically, triggering the movement of each foot.
Based on an Intelligent algorithm	Intelligent algorithms such as neural networks, fuzzy control and genetic algorithms are used in gait planning to enhance the robot's learning ability and adaptive ability during walking.
Based on the model	The complex robot system is simplified into a relatively simple model using solving the problem and reducing the order.

through decoupling and order reduction. Chang et al. investigated the stability of a biped robot's turning attitude, landing stability, and the planning and control of landing after turning [41]. They improved the inverted pendulum model and introduced a rotation angle into the trajectory generation model to realize gait planning. The main gait planning methods are summarized in Table 2.

Although previous approaches can be used to plan a free gait suitable for diverse terrains, the planned gait remains rigid. However, there is a gap between its performance and that of animal gaits, and most gait-creation algorithms are designed solely for specific robots. When a robot encounters obstacles or faults during motion, its topological structure changes, and it is challenging for the original gait generation algorithm to generate a stable gait. The environmental adaptation of hexapod robots is complex on an unstructured continuous ground. Previous research has concentrated on gait planning techniques to improve the inherent capabilities of leg robots walking on medium terrain. Therefore, the current leg robot can quickly become stuck and fall when encountering continuous unstructured terrain. Chen et al. proposed a hierarchical control framework for posture transitions in wheel-legged robots based on flexible posture planning and behavior rules. The framework presented in this study addresses the challenges related to posture, trajectory planning flexibility, and leg payload in unstructured terrain for arthropod robots. Future research should focus on designing a distributed control system to enhance further the mobility and stability of arthropod robots [42]. A mechanism for gait switching was proposed to allow the hexapod robot to create several gaits to adapt flexibly to complex terrains [43]. This study described the connection between the gait topology of six-legged robots and physical restrictions, such as robot stability and terrain interference. The suggested gait switch can generate 0–6, 1–5, 2–4, and 3–3 gaits according to stability and interference requirements. The robot scaled 45-degree stairs with success, thereby proving the effectiveness of the gait-switching strategy. Animal gait is usually controlled solely by a central pattern generator in the lower nerve center as a rhythmic behavior. With the assistance of an advanced nerve center, real-time planning and learning may be performed in response to specific surroundings to recall the gait that adapts to the terrain when traversing an unknown and complex terrain. Locomotion and learning behavior rhythms allow animals to cross diverse and complicated environments efficiently and safely. Therefore, gait planning based on rhythm and learning behavior is a significant concern in multilegged robot gait planning.

Gait planning for a walking robot is a core control issue in robot walking; therefore, it has significant research value. However, gait planning faces the following problems:

a. Insufficient stability of gait motion. Robots are prone to losing balance or falling in complex environments, leading to mission failures.
b. Normal robot walking with poor gait adaptability is affected by multiple factors (such as ground conditions and mechanical structure), and it is difficult to adapt existing gait planning algorithms to these different factors.
c. Planning a gait that can be adapted to dynamic environments is challenging. In practical application scenarios, the robot must adjust its gait plan according to environmental changes at any time. However, traditional gait planning methods often require a response to dynamic environmental changes.

The following remedies may be given for the issues above:

Online optimization methods, such as predictive control methods for motion planning, have been introduced to achieve dynamic gait planning. These methods can directly respond to environmental changes and dynamics:

a. Control requirements, thereby improving robot performance.
b. Adopt modern control methods, such as machine learning, combined with much experimental data, to establish accurate and reliable models to adapt to different environments and varying load/attitude control requirements and improve gait stability.
c. The focus has gradually shifted from rigid to flexible robots. Variable-stiffness plastic materials are used to achieve gait robustness. Increase passive control components (springs and dampers) to improve gait adaptability.

In conclusion, gait planning for walking robots is a complex problem that requires the consideration of multiple factors. The introduction of online optimization, machine learning, and flexible robot structures is a crucial research direction for improving the robustness and adaptability of gait planning. Future research should focus on developing more intelligent gait-planning algorithms that enable robots to adapt to complex and variable environments while efficiently performing tasks.

Gait planning for multilegged robots on complicated, unstructured terrain was achieved through free gait. Cognitive learning and Central Pattern Generator (CPG) algorithms have been studied extensively in this area. With advancements in electronic hardware technology, artificial intelligence, robot control, traditional planning, and advanced intelligent control algorithms have been used to enhance the intelligence level and motion performance of robots in response to increasingly complex-task scenarios. In addition to leg lifts, a detailed foot-space trajectory of a robot walking in a complicated and unstructured environment is essential.

B. FOOT TRAJECTORY PLANNING OF WALKING ROBOT

Foot trajectory planning is an essential element of a walking robot's motion planning and is one of the determinants of its motion control performance. Currently, planning a walking robot's foot trajectory is primarily divided into two categories: leg end planning in the task space and leg joint planning in the joint space. Regardless of the type, offline and objective optimization-based trajectory-planning approaches are the most frequent.

In the offline planning method, the trajectory of each leg or joint is planned and stored in the robot by a polynomial curve, compound cycloid, and B-spline curve in advance and can be called when needed [44]. Several studies used foot trajectory planning based on compound cycloids. Sakakibara et al. proposed a foot trajectory method based on a compound cycloid and verified its effectiveness in quadrupedal robots [45]. The basic formula for a compound cycloid is given by Eq. (2). where S is stride, H is leg height, and T_m is swing phase. Chen et al. designed a new electric leg mechanism for quadrupedal robots and proposed an improved foot trajectory based on compound cycloids [46]. The trajectory exhibited swing and retraction motions and continuous velocity along the x-axis. The effectiveness of the trajectory is verified through simulations and experiments.

$$\begin{cases} x = S\left[\dfrac{t}{T_m} - \dfrac{1}{2\pi}\sin\left(\dfrac{2\pi t}{T_m}\right)\right] \\ y = H\left[\dfrac{1}{2} - \dfrac{1}{2}\cos\left(\dfrac{2\pi t}{T_m}\right)\right] \end{cases} \tag{2}$$

The motion of the swinging leg is limited by the location of the landing point, terrain, and other constraints, which have different effects on time, speed, acceleration, and energy consumption. As a result, a significant proportion of academics view the management of their time and energy consumption as crucial optimization goals. For example, a collision-free and energy-efficient method for optimizing the trajectory of a robot's swing limb has been proposed to enable the robot to traverse rough terrains. Experiments with a Pegasus robot traversing obstacles such as steps, slopes, and stairs automatically validated the efficacy of the proposed algorithm [47]. Wu et al. designed a trajectory that can meet the requirements of a one-leg jump and minimize driving energy consumption by studying the influence of a one-legged robot on ground foot impact and jump constraints [48]. Xia et al. proposed a three-element trajectory-determination method [49]. The three elements are the starting point of the supporting phase, the endpoint of the supportive phase, and the change in the joint angle in the transfer stage. In this method, the support phase is planned in Cartesian space, and the swing phase is planned in joint space. In conjunction with the change in the joint angle during the transfer phase, control over the moving process height, distance, and direction is achieved. Thus, a foot trajectory enabling the robot to walk adaptively was generated. Zeng et al. designed the foot trajectory of a quadrupedal robot with a high-speed trot gait [50]. This trajectory minimizes the maximum acceleration of the leg and ensures continuity of position, velocity, and acceleration.

In summary, leg-end trajectory planning using a compound cycloid provides a readily adjustable solution that satisfies the offline deployment requirements of the trajectory. Conversely, trajectory planning that optimizes time and energy consumption prioritizes eco-friendliness and addresses performance parameter optimization. Although the offline foot trajectory planning method is straightforward and user-friendly, it prevents the robot from following a predetermined trajectory, limiting its adaptability to complex environments. The foot-end trajectory planning method, which utilizes goal optimization, builds on simple trajectory planning by imposing constraints to attain the desired optimization goal. This online planning method is typically equipped with real-time capabilities and can be adapted to complex environments. However, the planning process involves several calculations. In complex environments, computing issues may lead to reduced real-time performance, which can undermine the stability of the walking robots. Thus, future research on foot trajectory planning should address the computational challenges that impact real-time performance and, consequently, the stability of robot walking.

In addition, multilegged robots walk on complex unstructured ground, and force perception plays a vital role in real-time body control. Next, we analyze the research status of robot force sensing and provide an alternative breakthrough direction for force sensing.

C. FORCE PERCEPTION TECHNOLOGY OF WALKING ROBOT

The primary functions of a walking robot's force perception technology are twofold. One is the pressure control function, which maintains the active adaptation of the plantar surface to ground pressure as the robot walks on rugged unstructured terrain. The second purpose is to control the robot's speed change, which ensures a seamless transition.

Many scholars have realized the measurement and perception of foot forces by designing sensors or sensor systems. Chen et al. proposed a hybrid walking and obstacle avoidance control strategy for six-wheel-legged robots in rugged terrain. This strategy uses a visual recognition system to select appropriate hybrid walking types and parameters. The feedback controller combined the attitude and force sensors at the end of the robot's legs to maintain the attitude of the body. This study demonstrated the effectiveness and feasibility of hybrid walking and obstacle avoidance control strategies. Future research directions include active vibration isolation, hybrid adaptive control, or machine learning to improve the system's robustness [51]. The HITCR hexapod robot Harbin Institute of Technology developed a bamboo worm as a bionic prototype [52]. The force sensing system of the leg installs the torque sensor at the basal joint and the basal femoral joint and installs the three-dimensional force sensor at the foot end. The system can sense and respond to the external force at any leg position and realize the interaction between the robot and the external terrain environment. The Big Dog quadrupedal robot developed by Boston Dynamics converts infinite complex terrain conditions into a finite number of planes that can be divided according to angles [53]. First, the plane the current supporting leg determines is the hanging step leg. Second, incomplete motion planning was implemented for the most likely landing plane, and the change in the pressure sensor reading was used to determine the foot contact between the suspended leg, stampede leg, and ground. Using a simple pressure sensor, the robot can obtain interactive information between the foot and the ground.

Some scholars do not use external sensors but indirectly estimate the interaction force between the foot and ground by designing controllers. Zhang et al. proposed an estimation method that uses foot contact force based on generalized momentum [54]. They applied a contact force to the robot impedance control to realize the active compliance control of the robot. This method can predict the contact force between the foot end of the robot and the ground without a force sensor; therefore, it is convenient to apply. However, this method is unsuitable when a sufficient force must be measured accurately. Bjelonic et al. designed a hexapod robot weaver using a hierarchical controller (including impedance and tilt controllers) [55]. In the impedance controller, the robot does not measure the contact force between the toe and the ground using a conventional force sensor. Instead, the contact force was calculated using the current signal of the motor.

Starting with the foot of the robot, some scholars have combined all types of sensors with the designed foot structure, which can not only measure the foot force but also obtain the local terrain information of the foot. Gálve et al. proposed a robot foot and ankle design using an integrated sensor system [56]. It connects two rotary potentiometers to each axis of a universal joint (the ankle of the robot) to measure the two angles that define foot direction. The distance between the current landing direction and the ground can be used to determine the direction of the local terrain under the foot. Lee et al. proposed an active sensing method for estimating the edge of the contact terrain using the geometric information of robot connecting rods [57]. First, a Hammer T-sensor installed in the ankle joint was used to determine whether the robot was in contact with the ground. The virtual Center-of-Pressure (v-CoP) concept is used to generate active sensing motion to make the robot rotate on the ground and keep in touch with the ground while collecting the geometric information of the contact rod. The geometric shape of the ground was estimated using the data measured by the encoder installed at each joint angle, and the edge line of the terrain under the robot foot was predicted by solving for the intersection of the contact foot plane. Valsecchi et al. designed a new type of sensing foot [58]. It integrates a six-axis force/torque sensor and an Inertial Measurement Unit (IMU) with a passive ankle joint with two degrees of freedom to realize the perception of ground tilt at contact and the measurement of the local reaction force. Qi et al. proposed a new multi-sensor data fusion model for interference recognition in the presence of occlusion. They compared the classification performance and prediction time of the Long Short-Term Memory - Recurrent Neural Network (LSTM-RNN) model with several traditional machine learning algorithms such as K-Nearest Neighbors (k-NN) and Support Vector Machine (SVM). They found that the LSTM-RNN classifier had a higher recognition rate and faster inference speed, and the adaptive data fusion system had strong anti-interference ability for real-time gesture recognition [59]. By comparing the design schemes and advantages and disadvantages of foot force sensors mentioned in several literatures, we conclude that interested parties can fully draw on the adaptive data fusion system to design a multi-sensor system with the strong anti-interference ability for real-time gait recognition.

Additionally, Qi et al. studied breathing patterns using a Wearable Breathing Pattern and Activity Monitoring (WRAM) system. Their novel multi-complex sensing system proposes a Hybrid Hierarchical Classification (HHC) algorithm that combines deep learning and threshold-based methods to distinguish complex activities, thereby improving system accuracy and speed [60]. The complex sensor system has demonstrated good real-time detection of the motion state for the motion control system of the multilegged robot, indicating its potential for further integration and innovation.

In summary, foot force perception is essential for walking robots to maintain active adaptation to rugged terrain and ensure seamless transitions in speed. Researchers have designed various sensors and systems to measure and perceive foot forces, including torque, six-dimensional forces, pressure, and virtual center-of-pressure sensors. Some scholars have designed controllers to estimate the interaction force between the foot and the ground. Other scholars have integrated various sensors into the design of foot structures to measure the foot force and obtain local terrain information.

However, there are some limitations in this field. For example, some methods are unsuitable for accurately measuring sufficient force and a unified standard for foot force perception is lacking. We suggest more effective and accurate methods for measuring foot force and propose establishing a unified standard for foot force perception. Moreover, we recommend optimizing the integration of various sensors to achieve better performance and ease of use.

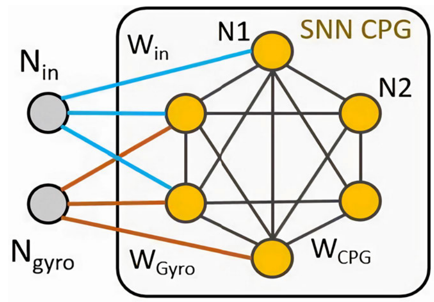

FIGURE 5. Network architecture [61].

D. TYPICAL EXAMPLE OF OPEN-SOURCE ROBOT'S SMOOTH MOTION

In mobile robots, legged robots have great potential as rising stars. While the hardware implementation difficulty of legged robots is no longer a problem, given the current manufacturing capabilities, representative control algorithms and software technologies for functionality remain a research focus. As one of the representatives in the development process of control algorithms for legged robots, the CPG control algorithm plays an important role in promoting research progress.

Building on the literature on CPG control for multilegged robots, this paper explores the pivotal directions for developing biologically-inspired robot motion control systems. We present a case study using literature from 2022 [61]. The present study makes two key contributions. Firstly, a lightweight algorithm is proposed for programming spiking patterns in recurrently connected spiking neural networks for multilegged locomotion. Secondly, the first closed-loop end-to-end robotic system with spiking neural network-driven data processing from visual sensory data acquisition to locomotion is demonstrated. This work paves the way for advanced applications of intelligent bio-mimetic robotics.

The present study introduces an innovative methodology for training legged robots to walk using the Spike Neural Network (SNN) framework. The authors synergistically combine the SNN architecture's efficient processing capabilities with the synchronous patterns generated by Central Pattern Generators (CPGs) to deliver comprehensive end-to-end learning for mobile robots. To this end, they introduce a reinforcement-based technique that employs random weight updates to train peak CPGs, as illustrated in Fig. 5.

Six-legged robots are driven by six Leaky-Integrate-and-Fire (LIF) spiking neurons in a CPG network. W_{in}, W_{Gyro} and W_{CPG} represent the weight matrices corresponding to the all-o-all connection. N_{gyro} is a neural element driven by a gyroscope sensor. A flowchart detailing the structure of the study is presented in Fig. 6. The inspiration for the bionic edge robot intelligent control model is illustrated in Fig 6 (a), which depicts the perception of drive in a hexapod insect. The insect's sensory information is obtained and processed by impulse neural circuits in the brain, stimulating motor neurons that facilitate movement. The rhythmic activity of these motor neurons leads to the formation of coordinated muscle movements and thus gait. Fig. 6(b) displays a bionic electronic prototype of a hexapod robot controlled by a spiking neural network. Fig. 6(c) illustrates six fully connected neurons, where the peak of one neuron triggers the corresponding leg movement. During the execution of specific tasks, the hexapod robot inevitably needs to switch gaits to alter its speed and direction of motion. Adjusting the synaptic weights in the neural network generates a specific sequence of spikes, leading to the corresponding gait. This study applied a supervised weight adaptation method to a single Spinal Central Pattern Generator (SCPG) to plan multiple gaits, as demonstrated in Fig. 6(d). The SCPG is a neural circuit that generates rhythmic patterns of motor activity, essential for coordinating leg movements in hexapod robots. To achieve this, the researchers constructed an end-to-end comprehensive exploration framework for the hexapod robot system, as shown in Fig. 1(e)-(i), which includes a bionic hexapod robot system, an SNN processing network, an SCPG gait generator, and a closed-loop feedback circuit event flow system. The SNN network processes event data from Dynamic Vision Sensor (DVS) to drive the gait, and the SNN for edge detection separates multiple targets from each other, as shown in Fig. 1(e).

The closed-loop feedback circuit adjusts the synaptic weights in the SCPG based on the error signal between the desired and actual gaits, enabling the SCPG to adapt to changing environmental conditions and achieve robust locomotion. The present study introduces an end-to-end neural morphology system that acquires event-based visual data from a dynamic vision sensor and generates adaptable gait patterns for hexapod robots in predator-prey tracking scenarios. The method is entirely biomimetic, achieving perception-driven locomotion through event-based processing. To learn multiple gaits, a supervised weight adaptation algorithm was introduced, which learns multiple gaits in a single CPG. This demonstrates the feasibility of the end-to-end neural morphology system for resource-constrained edge robots. The proposed neural morphology CPG was applied to a hexapod robot, achieving biomimetic walking gaits through energy-efficient online reinforcement learning. The online learning system was implemented on a resource-constrained embedded system. The learning process converged in 70% of cases, while in other cases, it converged to suboptimal

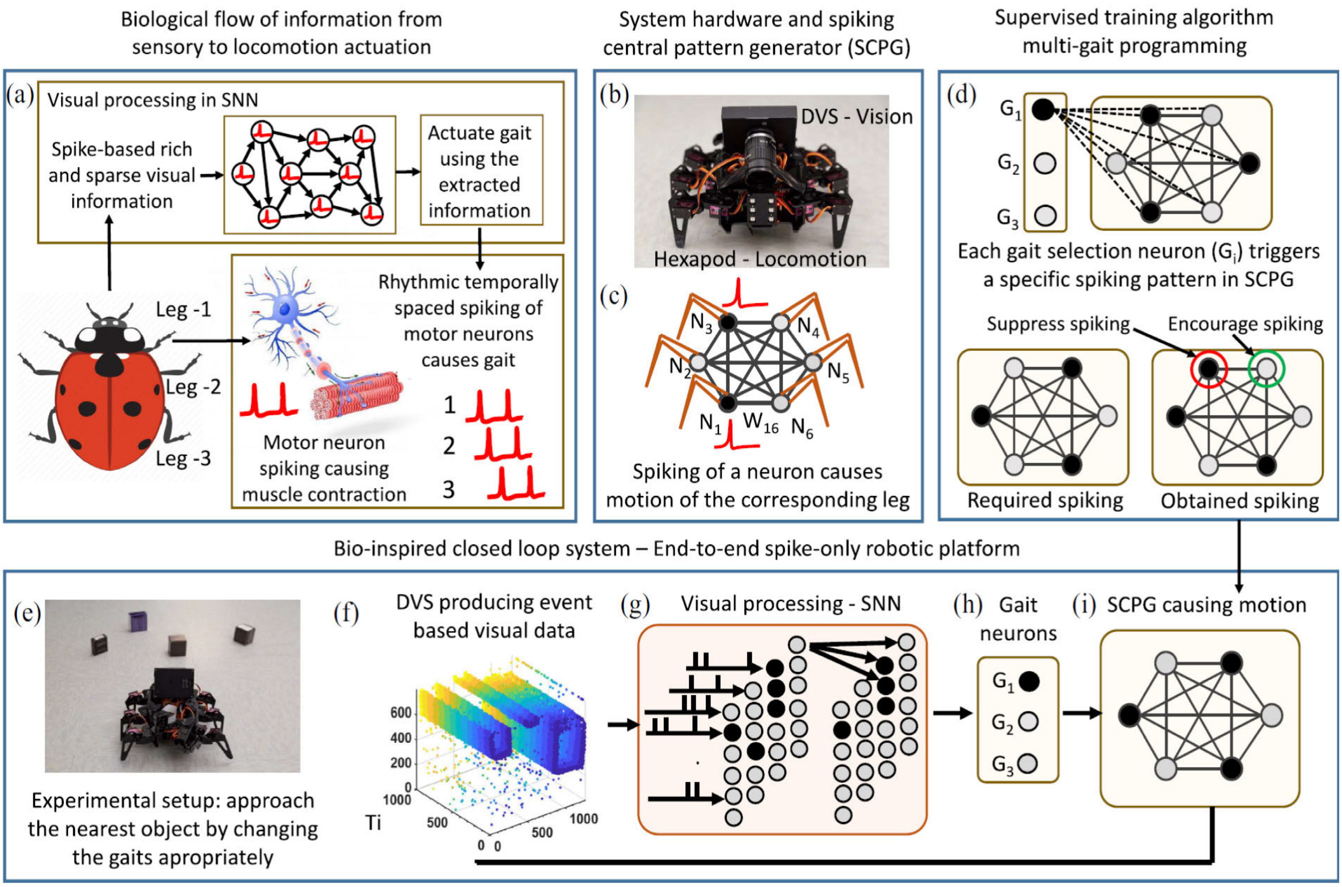

FIGURE 6. **Process diagram of edge robot research based on SNN-CPG control [61].**

gaits that still enabled movement. Overall, the framework presented in this study provides a promising approach for developing advanced hexapod robot systems with improved adaptability and robustness in complex environments.

From an engineering perspective, Hexapod robots are highly dynamic, adaptable, stable, robust, and strongly coupled and nonlinear, complex, dynamic systems. The CPG neural circuit is a distributed system of mutually coupled, nonlinear oscillators that generate rhythmic signals by coupling their phases. Varying the coupling between oscillators results in spatiotemporal sequences with distinct phase relationships, leading to diverse motion patterns. The advantages of third-generation pulse neural networks over first-generation perceptrons and second-generation deep neural networks lie in their more significant biological similarity. In theory, pulse neural networks should also have superior computational speed and resource utilization compared to the currently used second-generation neural networks. Peak neural networks of biologically inspired network models typically use central pattern generators for producing oscillatory movements, such as walking in biological systems. However, because pulses lack differentiability, it is impossible to update the parameters of neurons using the BackPropagation (BP) algorithm. Current parameter updating methods have proven inadequate in achieving the desired effect. Therefore, pulse neural networks face many challenges in developing CPG-based legged robots, a promising field.

E. SUMMARY AND SUGGESTIONS

This section discusses methods for planning the movement of multilegged robots, including path formulation rules, bionic motion rhythms, and fusion neural network algorithms. The CPG algorithm is the most practical for robot movement; however, it requires assistance in learning in unstructured environments. Foot trajectory planning methods include offline deployment and goal optimization, with the latter being more adaptable to complex environments but requiring more calculations. Force perception is critical for real-time body control, with various sensors and systems designed to measure foot force. However, research limitations and challenges remain, and we recommend further research on more effective and accurate foot force perception methods and uniform standards.

At present, if we want a robot to have the ability to cross rugged terrains, it generally starts from three points:

1) The robot body mechanism was improved using a mechanical design to adapt to the rugged terrain.

2) There is good interaction between the robot and rugged terrain by controlling the contact force between the robot's leg and the ground.
3) By utilizing force-sensing technology and terrain reconstruction strategies, a robot can obtain information regarding the ground beneath its feet, thereby facilitating the selection of landing points. Tactile and visual feedback enabled the robot to perceive the terrain and environment.

Two main ways exist to realize the force between the robot leg and the ground. The first is to sense foot force through external perception, such as foot force sensors. The second method involves calculating or estimating the foot force.

The foot-end trajectory of the robot was determined using Bezier curves and trajectory planning techniques. Although the control method is simple, adapting to changing terrain poses a significant challenge, and gait planning and foot-force control require higher-level supervision. A common approach is to design a controller that can acquire contact information between the robot leg and the ground without external sensors. However, to achieve fluency, robustness, and self-stability in the dynamic time-varying interaction between the robot and the environment, a compliant controller should be incorporated into the control system, which is the main focus of this study.

III. ACTIVE COMPLIANCE CONTROL OF QUADRUPED ROBOT

Owing to the challenges of unstructured terrain motion, conventional position controllers cannot satisfy the requirements of robustness and self-stabilization in the dynamic time-varying interactions between quadrupedal robots and their surroundings. This is because unpredictable foot-ground impacts generated by terrain undulations are inherent in the workplace. The position control method tracks the planned foot trajectory using the kinematics of the robot while considering the interactive information between the robot and the ground to achieve impact flexibility. Some researchers have developed a smooth curve technique to reduce the effect on the ground; however, this relies on positional control and requires adjustment of the planned foot trajectory based on the stable walking of the robot. Therefore, compliance control has been one of the primary studies of contemporary scholars as a critical problem for solving the future applications of robots [62], [63]. The control system should introduce a soft control method to achieve a smooth interaction of the four-legged robot movement. Next, we focus on impedance, virtual models, and active compliance control methods.

A. IMPEDANCE CONTROL

Researchers have discovered that controlling each leg is essential for controlling multilegged robots. This implies that the one-leg system is most significant in determining the robot's movement. Flexible active compliance control methods are used for multilegged robots to satisfy the increasing demand for reliable structures and versatile motions.

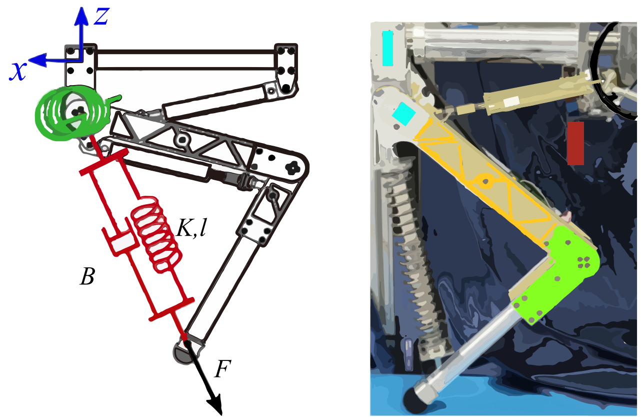

FIGURE 7. One-leg compliance scheme of HYQ quadruped robot 1985.

He et al.realized the active coordination of the force-position relationship through the feedback of the force sensor and designed a virtual spring-damping model at the software algorithm level to simulate the compliance characteristics of a natural spring damper [64]. Boaventurah et al. compared the active and passive compliance of HYQ robot legs on a one-leg test platform [65]. The results demonstrated that a system with active compliance control could imitate the effects of a system based on passive components. As shown in Fig. 7, this provides a solid theoretical basis and scientific proof for the robot to apply active compliance, and provides a basis for realizing the compliant motion of a rigid body.

According to the energy transfer direction classification, when the robot is in contact with the environment, the American scholar Hogen adopted an energy bond graph to divide the force control into impedance control and admittance control [66]. Impedance control is a technique in which the robot's driving force is modulated based on the robot's position deviation to regulate the contact force between the robot and the environment. This technique allows the robot to achieve compliant behavior, essential for safe interaction with humans and delicate objects. The impedance control approach considers the robot as an impedance network, where the input is the desired motion trajectory, and the output is the motion of the end effector. The impedance parameters can be adjusted to control the robot's stiffness, damping, and inertia properties. Impedance control is a promising approach for achieving precise and safe robot-environment interactions. Admittance control measures the contact force between the robot and the environment to adjust the robot's posture to control the contact force between the robot and the environment. In this study, foot-ground contact force control is divided into impedance control and admittance control, which promotes research on impedance control in robots.

Impedance control in multilegged robots realizes flexible interactions between robots and the ground [67], [68]. Sun et al. at Shanghai Jiaotong University designed a position-based impedance controller to realize active compliance with the variable impedance parameters on each leg of the robot

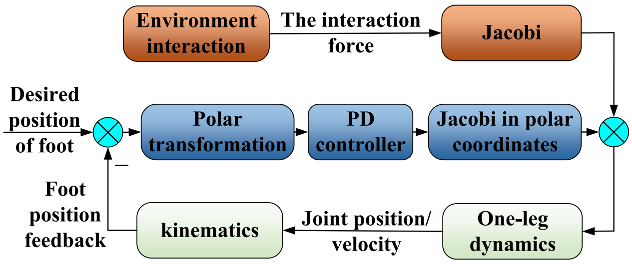

FIGURE 8. **Compliance control method.**

[69]. The hexapod robot's three-legged alternating gait state machine was designed based on active compliance. Wang et al. proposed a hierarchical framework to achieve flexible motion under a load in six-wheeled leg robots, enabling the robot to adapt effectively to different terrains. In the future, this framework will be optimized for mechanical design and studied for multi-information fusion systems to enhance the stability of robots in constrained environments [70].

Based on the concept of active compliance, the compliance characteristics of each leg were adjusted in real-time according to the gait state, and a multimode impedance control strategy was realized. In addition, the University of National Defense Science and Technology proposed a force estimation method based on robot generalized momentum that improved the speed and accuracy of force estimation [71]. The estimated contact force was applied to the multilegged robot's impedance control, and the robot's active compliance control was realized. This study promotes the application of impedance control by improving the accuracy of force estimation. Other scholars have conducted related research on the torque of the motion switch and the driving current of the joint, which promotes the development of impedance control. For example, Seok et al. designed a motor driver with ontology sensing ability to realize joint torque control without a force sensor [72]. Based on this, MIT Cheetah demonstrates a good compliance performance and can run quickly. This method skillfully replaces the force sensor function by measuring the motor driver current to calculate the foot force, as shown in Fig. 8 (summarized in the literature [72]). Kerimoglu et al. also controlled the motion of a small dog based on a joint motor current servo that could adjust the position-control stiffness, and the robot demonstrated good immunity and terrain adaptability [73].

In summary, the core idea of impedance control is to measure the difference between the current and target positions (such as the joint current) and adjust the force generated at the end. The flexibility of the end of the robot was adjusted according to the dynamic force–position deviation relation. Among them, for position control, such as handling, welding, and spraying robot motion control, the control variables are (angular) displacement, (angular) velocity, and (angular) acceleration. Force controls, such as grinding, polishing, assembly robot operation control, and the Boston power robot, are suitable for walking, running, jumping, somersaulting, and snow walking.

This section discusses the current trend of utilizing active compliance control methods for multilegged robots, which allow flexible interaction between a robot and its environment. However, there are limitations to the force control, and this section recommends the use of impedance and admittance control methods. Impedance control adjusts a robot's driving force and position to regulate its contact with the environment, whereas admittance control adjusts the contact force to control its posture. Improving the force estimation method is crucial for achieving a more accurate impedance control. This section also highlights studies on joint torque control without force sensors, which facilitates the development of impedance control. Future research can focus on applying active compliance control in more complex environments such as rough terrain or downhole exploration.

Further, damping control is a direct control force but requires a powerful sensor at the end. Admittance control controls the force by controlling the position, similar to Virtual Model Control (VMC), that is, through the position error driving force. The core idea of the VMC is to explore a simple control method for complex dynamic problems and simplify the processing of complex terrains. VMC control can not only solve the problem that the foot trajectory set by the Bessel curve is difficult to adapt to changing terrain, but also deepens the application of impedance control. Next, we research the VMC control, which is a type of impedance control.

B. VIRTUAL MODEL CONTROL

In the 1990s, Jerry, who worked in the MIT laboratory for multilegged robots, proposed the use of virtual model control. Motion control generates the joint torque required to control the virtual components. Attaching the simulation component to the robot makes it possible to achieve control, because this joint torque has the same effect as the virtual element. A virtual model control system can manage both compliant interactions and fuselage stability control on a floating fuselage with six degrees of freedom. By using the virtual spring-damping model in the floating fuselage and inertial coordinate system, the compliance and adjustment of the fuselage were achieved, and it was validated in the biped robot's walking control [74]. VMC has three apparent advantages:

1) Complex tasks can be described easily using simple virtual components. For example, HyQ uses a virtual model to implement a robot stability control. Two virtual spring-damper components between the torso and contact surface were used for VMC modeling. The virtual force and moment were calculated and converted into the feedforward torque driven by the joint of the supporting leg [75], [76], as shown in Fig. 9.
2) The small amount of calculation.
3) By using adaptive learning elements [77], [78] and stiffness control [79], the VMC can be easily extended to perform complex control tasks. The mathematical

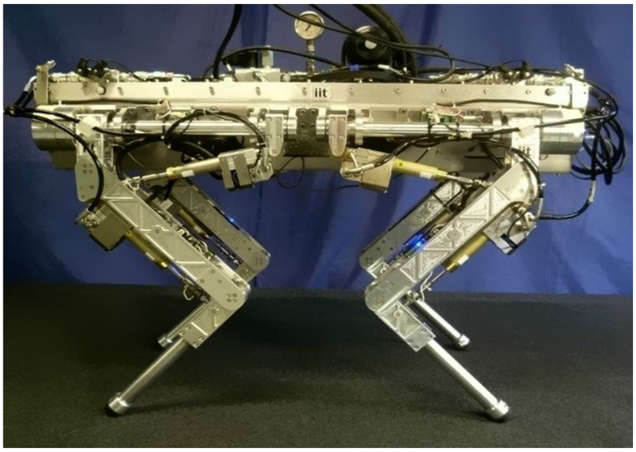

FIGURE 9. HyQ Robot Model based on VMC.

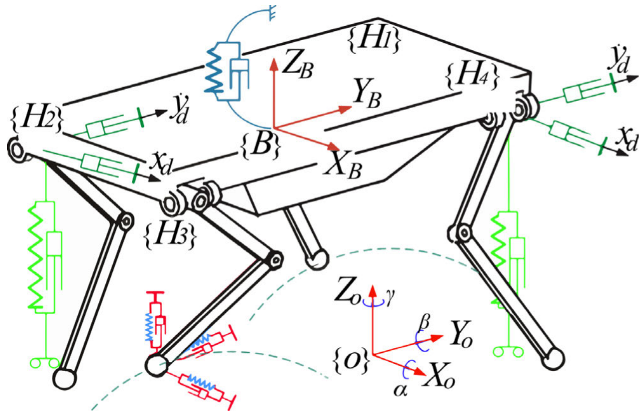

FIGURE 10. Decomposed virtual model control.

model of the VMC combined with multilegged robot motion control is shown in Eq. (3), (4), (5), and (6). The workspace-to-joint space position mapping connection is represented by Eq. (3). The Jacobian matrix shown in Eq. (4) transforms the joint velocity into the positional velocity of the body. The link between the external force and joint moments derived from the principle of reversibility of virtual work is represented by Eq. (5). The intrinsic equation for the virtual force is given by Eq. (6): In multilegged robot motion control, the primary virtual building blocks commonly used are springs and dampers. Virtual forces are directly linked to higher-level control decisions (desired displacement and velocity), making it easy to execute upper-level commands and achieve complex motion.

$$x = f(q) \tag{3}$$

$$\begin{cases} \delta x_1 = \dfrac{\partial f_1}{\partial q_1}\delta q_1 + \cdots + \dfrac{\partial f_1}{\partial q_n}\delta q_n \\ \vdots \\ \delta x_m = \dfrac{\partial f_m}{\partial q_1}\delta q_1 + \cdots + \dfrac{\partial f_m}{\partial q_n}\delta q_n \end{cases} \tag{4}$$

$$\begin{cases} \tau^{\mathrm{T}}\delta q + (-F)^{\mathrm{T}}\delta x = 0 \\ \delta x_{(m\times 1)} = J_{(m\times n)} \cdot \delta q_{(n\times 1)} \\ \tau = J^{\mathrm{T}}F \end{cases} \tag{5}$$

$$\begin{cases} F_\theta = K_\theta\left(\theta_{\mathrm{d}} -\right) + B_\theta\left(\dot{\theta}_{\mathrm{d}} - \dot{\theta}\right) \\ \boldsymbol{K} = \begin{bmatrix} K_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & K_m \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} B_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & B_m \end{bmatrix} \end{cases} \tag{6}$$

The above equation $\boldsymbol{x} = \left[x_1\ x_2\ \ldots\ x_m\right]^{\mathrm{T}}$ represents the posture vector corresponding to the m degrees of freedom of the body coordinate system concerning the ground coordinate system, and $\boldsymbol{q} = \left[q_1\ q_2\ \ldots\ q_n\right]^{\mathrm{T}}$ represents the position vector of the n joint variables. $\boldsymbol{\tau} = \left[\tau_1\ \tau_2\ \ldots\ \tau_n\right]^{\mathrm{T}}$ is the joint moment column vector and $\boldsymbol{F} = \left[F_1\ F_2\ \ldots\ F_m\right]^{\mathrm{T}}$ represents the external force. F_θ denotes the force (or moment) generated by a virtual component. Where K_θ and B_θ are elasticity and damping coefficients, respectively. θ and $\dot{\theta}$ are the real-time displacements and velocities, respectively, in the appropriate generalized coordinates, and the subscript d indicates the predicted value.

Impedance control [80], [81] and VMC can be easily extended to perform complex control tasks. Gehring et al. established a mapping from the virtual force and torque on the torso to the force on the virtual leg, and subsequently to the joint torque [82]. They used this technology to control the entire body of the starleth robot. Xie et al. proposed a method for systemic motion control of a quadrupedal robot [83]. The decomposed virtual model control was combined with the Raibert method to adjust the body's height, speed, and posture directly during the standing stage. The swinging leg followed the planned foot trajectory, which could be adapted according to the robot's speed, as shown in Fig. 10.

This quadrupedal robot can move in all directions on flat ground using a diagonal trot gait, crossing uneven terrain, and resisting external impacts. However, in the support phase model of the robot, control of the lateral virtual force on the torso was abandoned. This may cause the robot to have difficulty maintaining balance. Therefore, future research should focus on improving the robot control system to better control its movement and posture, enabling it to adapt to different environments and tasks more efficiently. The lateral velocity of the torso is controlled by the motion of the swinging leg [84]. When a quadrupedal robot uses force to control its movement, it should satisfy the requirements of stability and balance of plantar and body forces. Therefore, a full-force distribution algorithm is essential for the force control of a quadrupedal robot. Zhang et al. of Shandong University analyzed the force control method based on the dynamic model of a quadrupedal robot and the force control method, whereas Zhang et al.of Shandong University analyzed the force control method. Fig. 11 and 12 depict an adequate force distribution method for the quadruped support stage and tripping support and a force control method based on

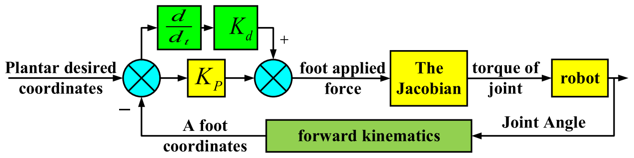

FIGURE 11. PD control block diagram of robot plantar motion space.

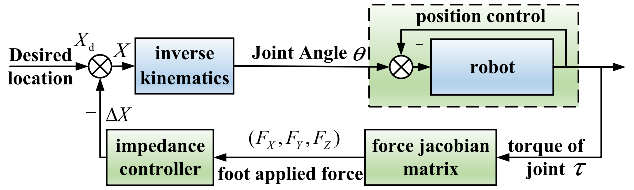

FIGURE 12. Admittance control block diagram of the robot.

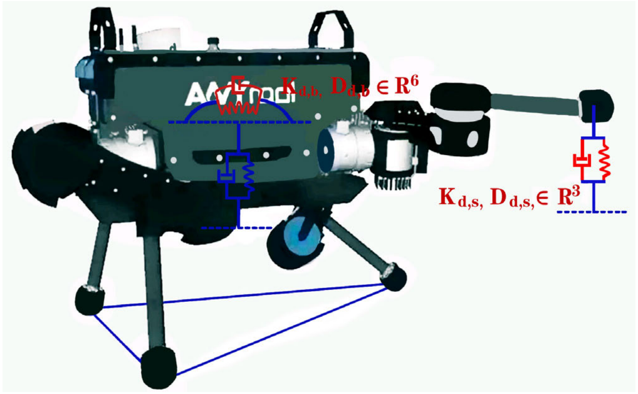

FIGURE 13. ANYmal Cartesian impedance controller model.

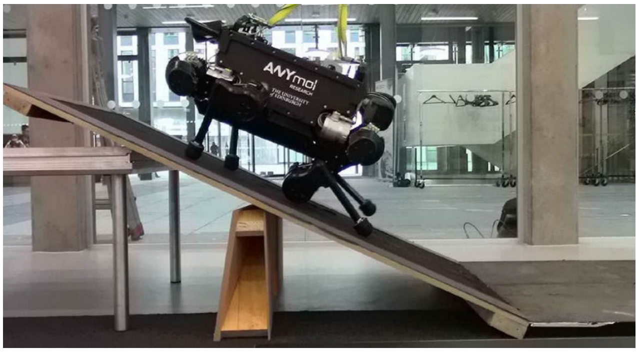

FIGURE 14. ANYmal climbing on a slope of 30°.

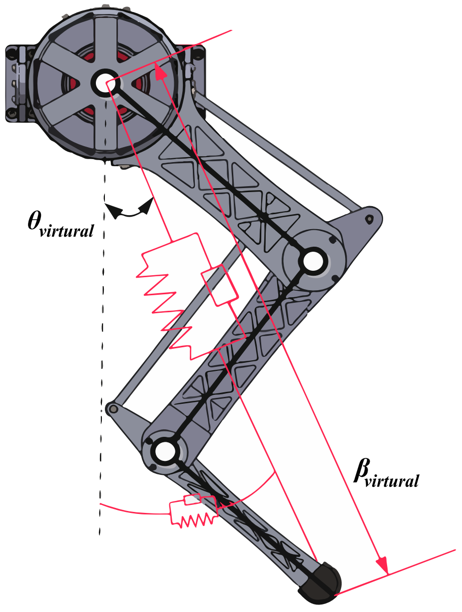

FIGURE 15. Single leg impedance model.

admittance control during robot motion. Applying the full force allocation method allows the robot to smoothly pass through rugged terrain according to gait planning.

Admittance control can improve the desired force-tracking effect of a quadruped robot [85]. Xin et al. proposed a semi-analytical motion controller [86]. The controller uses Cartesian impedance control to coordinate the tracking performance, the required compliance, and quadratic programming (QP) to satisfy the friction cone, unilateral, and torque constraints. The Descartes impedance controller (see Fig. 13) can track the desired end-effector trajectory and estimate external interference. Disturbance estimation was applied to model error compensation when the robot carried an unknown object. If the torque command required to track the trajectory does not satisfy the physical constraints, QP optimization ensures physical feasibility by sacrificing the trajectory tracking. The advantages of this trade-off strategy enable the robot to walk on artificial ice on a 30° slope (Fig. 14). Besides, compared to the controller based on complete optimization, the controller only needs to solve for fewer decision variables; therefore, the calculation time is negligible.

Du and Amar developed a zero-space-based compact torque controller with a manipulator for a high-wheeled quadrupedal robot [87]. The control problem was formulated as a linearly constrained quadratic programming problem (QP). The null-space-based inverse dynamics establish a close relationship between multiple task references and drive torque. We constructed a wheel-contact model of a wheeled quadrupedal robot using space vectors and integrated the wheel-contact force into each task formula. We developed a cost function for several operational space tasks and converted it into federated space. Several zero-space-based impedance controllers were integrated into close relationships to achieve task reference and compensate for model inaccuracies, particularly in wheel-rolling models. The simulation results demonstrate that the controller enables the quadrupedal-wheeled robot to exhibit rich versatility and dynamic behavior. The robot could efficiently and effectively handle complex tasks with unknown external forces.

Zhang et al.built a one-legged prototype and a test platform (see Fig. 15). The Cartesian coordinates of the foot were obtained by path planning, and the virtual polar coordinates of impedance control were obtained by geometric transformation. Finally, several experimental evaluations were performed using ground compliance identification, foot trajectory control, pure position control, and impedance control. The results demonstrated that impedance control could effectively solve the impact of the ground on the motor during the falling process [88].

Ding et al. proposed a new control algorithm for quadrupedal robots running on rough terrain, and model predictive control was introduced based on virtual model control [89]. In this method, the force distribution of the standing leg is calculated using a virtual spring-damping model through secondary optimization involving state prediction. The model follows the desired trajectory, and the two subcontrollers are composed of time-force-based state machines and are robust to external disturbances. The disadvantage is that position detection of the Center of Gravity (CoG) under the dynamic gait of a quadrupedal robot does not compensate for the CoG offset.

This section discusses the benefits of the VMC method, which can easily describe complex tasks using simple virtual components, requires minimal calculation, and can be extended to perform complex control tasks. Previous studies focused on applying impedance control and VMC to regulate the motion of multilegged robots, including full-force distribution algorithms and admittance control. However, challenges still exist in lateral virtual force control, force distribution algorithms, and compensation for the center of gravity offset during dynamic gait. Future research can focus on improving the control of these issues and applying impedance control and VMC to more complex environments, such as those with rough terrain and unknown external forces.

According to reviewed articles and studies, the VMC control algorithm manages the contact force using the virtual force generated by the contact position data. Active compliance control employs feedback information on the robot's force to control it actively. Therefore, we propose a control approach based on impedance and a virtual model to enhance the motion stability of multilegged robots. We used a force-based impedance control approach to regulate the leg swing phase, achieve precise trajectory tracking during the swing phase, and achieve compliant leg control. In addition, a virtual model control approach was used to regulate the support phase and achieve fuselage attitude control of the robot, ultimately enabling the stable walking of a quadrupedal robot. Our subsequent investigation involved an active compliance control method.

C. ACTIVE COMPLIANCE CONTROL METHOD

Because the quadrupedal robot's active compliance control approach continues the manipulator's control method, this study introduces four primary active compliance control methods: force-position hybrid control, parallel force/position, impedance, and admittance control. Table 3 presents the advantages and disadvantages of the proposed method.

Force control methods can be classified into direct and indirect force control methods. Force feedback that closes the force controller generates a loop for indirect force control. In indirect relay control, force control is achieved via motion control. This internal or external motion control loop can establish a relationship between the motion and the force of the system. The presence of a force sensor in a control system can be classified as display or implicit control. Force sensors for force feedback characterize direct force control. Simultaneously, in implicit cases, the actuator input is provided by open-loop control and the difference between the target and measured motions. Implicit force control is suitable only for reverse-drive systems with negligible friction effects [90]. Owing to its impact, the response characteristics are ideal only for low-speed and soft environment surfaces [91].

Stiffness and flexibility describe the static relationship, whereas impedance $I(s)$ and admittance $A(s)$ refer to the dynamic relationship between force deviation $E_F(s)$ and displacement $E_X(s)$, as shown in Eq. (7). Tables 4 and 5 present the formulae for the four types of active compliance controls.

$$\begin{cases} I(s) = \dfrac{E_F(s)}{E_X(s)} = A^{-1}(s) \\ E_F(s) = F_R(s) - F(s) \\ E_X(s) = X_R(s) - X(s) \end{cases} \tag{7}$$

The majority of compliance control techniques require the use of force sensors or observers to acquire the available force/torque data. As outlined in Tables 4 and 5, the control method is restricted to implicit impedance control if such data are unavailable.

The Active Compliance Control (ACC) method utilizes force control technology to adjust the robot's position, posture, and force in real time by monitoring sensor feedback signals, thereby maintaining smooth movement. This method enables robots to adapt to various force and position environments, while effectively avoiding the vibration and instability encountered by rigid robots. In terms of motion control for multilegged robots, The ACC method can achieve the following functions:

1) Collision protection: When the robot collides, the Active Compliance Control method can prevent damage by reducing stress and torque on the robot.
2) Terrain adaptation: Multilegged robots must walk on different terrains with varying shapes and friction characteristics. The active compliance-control method allows robots to adjust their stride and step frequencies according to different terrain environments to improve their movement efficiency and stability.
3) Load adaptation: When a robot carries loads of different weights, the Active Compliance Control method adjusts the motion, posture, and gait of the robot according to the weight and shape of the load to maintain stability and flexibility.
4) Energy efficiency: The Active Compliance Control method can improve the energy efficiency of the robots. This method can help robots conserve energy and operate on a single charge for extended periods by

TABLE 3. Analysis and comparison of the four active and compliant control methods [65], [66], [92], [93], [94], [95], [96], [97], [98], [99], [100], [101], [102], [103].

	Hybrid Force/Position Control	Parallel Force/Position Control	Impedance control	Admittance control
classification method	Explicit control	Explicit control	Explicit/Implicit control	Explicit control
	Direct control	Direct control	Indirect control	Indirect control
conception	The core is to use force control in some degrees of freedom and position control in the rest of the system to achieve the goal of comprehensive control.	The force and the output of the motion controller are superimposed to track the trajectory of the reference motion in the unconstrained direction and control the contact force in the constrained direction.	Achieve a goal relationship between force and motion, but not necessarily track their respective trajectories.	The input to the impedance module is the end force, which outputs the relative displacement offset. This offset is then added to the given displacement to generate the new displacement input for the position closed-loop.
advantage	• Force and position tracking in each subspace • Effective in a high-intensity environment • Independently designed and implemented position and force control law	• Force and position tracking • Robustness to (unpredictable) task changes	• No need to measure the force (Implicit control) • Robustness to task uncertainties (such as environment) and changes • Realize the motion/force relationship	• No reverse drive capability is required • No system/environment model is required • Acceleration is not required
disadvantage	• Force needs to be measured • Detailed environment models are required • Stability problems caused by discreteness	• Force needs to be measured • Dynamic is slower and more complex than the force-position method	• Unable to accurately track position and force • Reverse drive capability required • Sensitive to model error	• Force needs to be measured • Unable to accurately track position and force • Stability problem of low target impedance

TABLE 4. The first two compliant control formulas.

Hybrid Force/Position Control	Parallel Force/Position Control
$U(s)=S\cdot P(s)*(X_R(s)-X(s)) + (E-S)\cdot W(s)\cdot (F_R(s)-F(s))$ $U(s)$ Represents the output of the control whose position index is the x, the index of the force is f, $P(s)$ is the position control law, $W(s)$ is the control law of force, E is an identity matrix of size.	$U(\mathrm{s})=P(s)\cdot (X_R(s)-X(s)) + W(s)\cdot (F_R(s)-F(s))$ U(s) Represents the output of the control whose position index is the x, the index of the force is f, $P(s)$ is the position control law, $W(s)$ is the control law of force.

reducing unnecessary movements and adjusting the robot's motion according to the environment and load.

To facilitate positioning and support the selection of appropriate methods, Schumacher et al. [104] provided the options shown in Fig. 16.

D. TYPICAL EXAMPLE OF OPEN-SOURCE ROBOT'S SMOOTH MOTION

1) THE MIT SERIES OF QUADRUPEDAL ROBOTS

The MIT series of quadrupedal robots initially represents traditional control, utilizing the VMC algorithm. However, VMC has become inadequate with the increasing complexity of robots, tasks, and environments. As robot applications expand, VMC's limitations in control methods have become apparent. Against this backdrop 2019, MIT introduced the MPC-WBC (Whole-body Control) control strategy, which can more precisely control the robot's motion and posture, exhibiting superior performance in complex tasks. These control algorithms' continuous upgrading and improvement have led to steady improvements in MIT robots' motion control and path planning performance, enabling them to handle various complex tasks [105]. Additionally, Carnegie Mellon University's Quad-SDK project provides an exceptional open-source quadrupedal robot that is even more

TABLE 5. The latter two compliant control formulas.

Impedance control	Admittance control
$U_f(\mathrm{s}) = I(s)(X(s) - X_R(s)) + F_R(s)$ $U_f(\mathrm{s})$ represents the output of the control, mechanical impedance $I(s)$	$U_x(\mathrm{s}) = A(s)(F(s) - F_R(s)) + X_R(s)$ $U_x(\mathrm{s})$ represents the output of the control, mechanical admittance $A(s)$

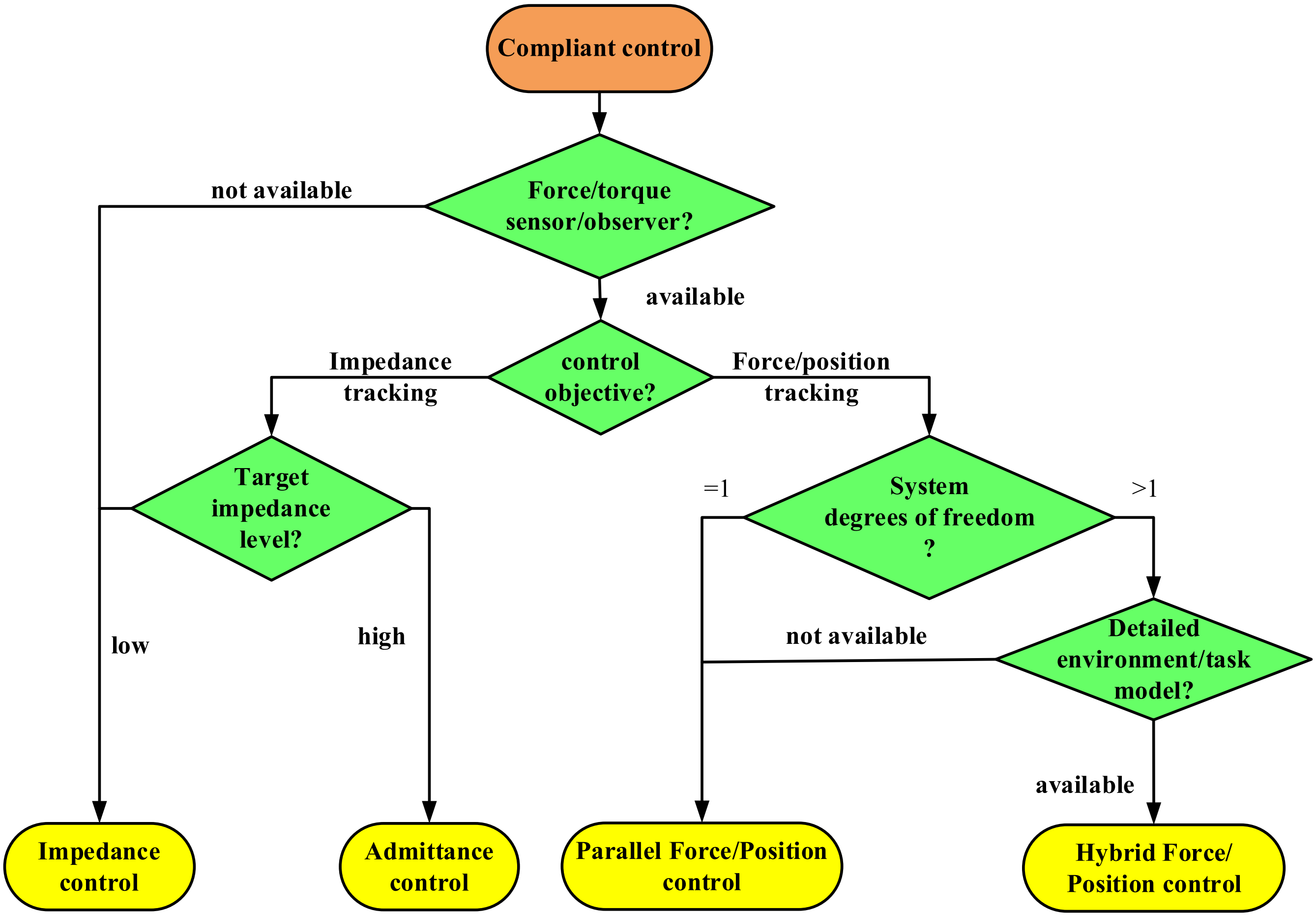

FIGURE 16. Selection scheme of active compliance control.

comprehensive and superior to MIT Cheetah, surpassing many others. The project adopts a nonlinear MPC controller [106].

The MOCO-8 framework utilizes MIT's early scheme based on VMC combined with quadratic programming decomposition (QP). The VMC+QP approach demonstrates moderate performance in terms of control effectiveness. When applied to typical trotting or standing gaits, the framework exhibits good control results while imposing low computational demands, as verified through physical robot experimentation. Under disturbed conditions, VMC can maintain at least two diagonal legs supporting every moment for the cycle-switching trot gait. However, control overshoot occurs and causes robot falls when all four legs undergo underactuated situations or leave the ground simultaneously. On the other hand, MPC offers superior capabilities in predicting future support scenarios by tracking the trajectory and proactively correcting the control input, leading to better stability maintenance of the robot.

2) THE QUAD-SDK OPEN-SOURCE PROJECT

To showcase quadrupedal robots' broadened active compliance motion ability under traditional control, we use the Quad-SDK open-source project as an example that surpasses the VMC and MPC control over MIT's quadruped robot. The Quad-SDK framework (see Fig. 17) can test and validate various quadrotor control algorithms in a Gazebo simulation

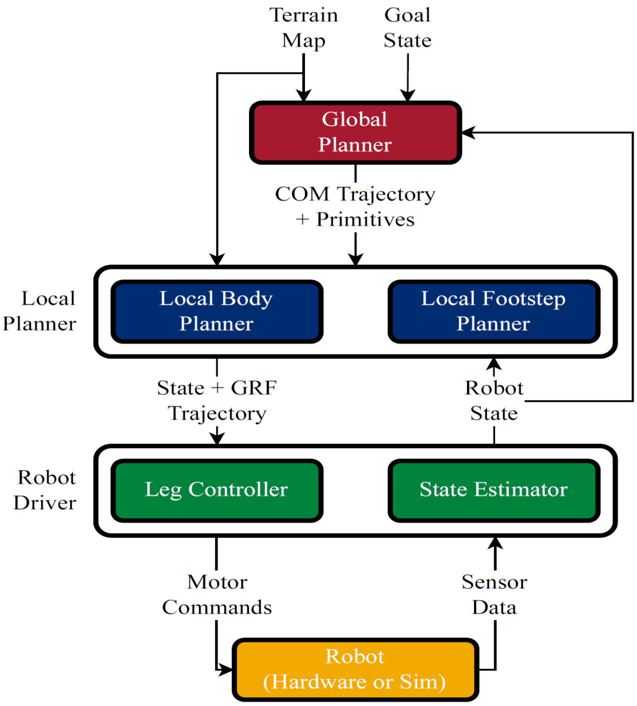

FIGURE 17. The Quad-SDK framework [106].

environment and deploy the developed algorithms on the Ghost Robotics' Sprite40 robot for real-world applications.

3) SEVERAL NOTABLE FEATURES OF THE PROJECT

This study presents several notable features. Firstly, it employs a nonlinear model (Eq. (8)) MPC controller, which was designed based on the relevant model presented in the literature [107]. The control performance of this project outperforms the open-source Mini Cheetah project. In the future, the NMPC-based approach will be the preferred research direction for bipedal and quadrupedal robots.

$$\begin{aligned}
&\min_{x,u} \sum_{i=0}^{N-1} \left\| x_{i+1} - x_{i+1,\,\mathrm{ref}} \right\|_{Q_i} + \left\| u_i - u_{i,\,\mathrm{ref}} \right\|_{R_i} \\
&\text{s.t.} \quad x_0 = x_{\mathrm{init}} \quad \text{(initial condition)} \\
&\qquad f\,(x_i, x_{i+1}, u_i, p_i, d\ t_i) = 0 \quad \text{(dynamic model)} \\
&\qquad x_i \in \mathbb{X} \quad \text{(state bound)} \\
&\qquad u_i \in \mathbb{U} \quad \text{(control bound)} \\
&\qquad C_i u_i \leqslant 0 \quad \text{(friction pyramid)} \\
&\qquad D_i u_i = 0 \quad \text{(contact selection)} \qquad (8)
\end{aligned}$$

Despite the nonlinear formula, the authors achieved over 100 Hz update rate for gait cycles using a novel hot-start method with 16 elements/cycle. They improved the hot-start quality by adjusting the initial finite element duration, enabling faster problem-solving over more extended periods.

Secondly, a more accurate terrain estimator was constructed in Quad-SDK, which can precisely model the terrain based on proprioceptive perception, surpassing the MIT open-source software, which lacks any components related to landing switching and terrain estimation (see Fig. 18). A long-term local gait planner was developed, which can plan the foot force and landing position for multiple future gait cycles, similar to the Atlas bipedal robot, surpassing the MIT framework, which only plans for the next gait cycle.

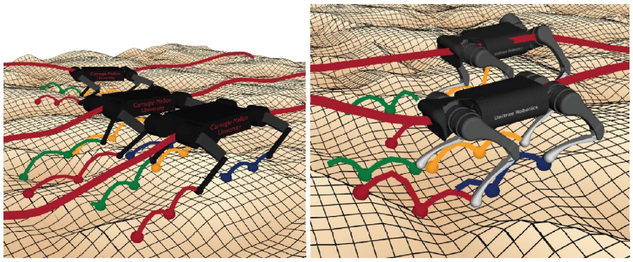

FIGURE 18. Planning of foot force and landing point in multiple gait cycles [106].

Quad-SDK enables unstructured motion for multiple agents, as demonstrated in the multi-robot support example shown in Fig. 18, which targets multiple platforms. This project has enabled robots to operate autonomously within a shared space, planning and executing multi-cycle trajectory environments. A global planner developed the first open-source online global trajectory planning algorithm for quadrupedal robots that incorporates terrain information and dynamic characteristics. This planner can plan the center of mass trajectory by combining expected waypoints, terrain information, gait parameters, friction coefficients, and kinematic constraints and can distinguish between support phases and flight phases in fine-grained global trajectories.

Based on our analysis of the innovation and effectiveness of the recently open-sourced Quad-SDK project in 2022, we believe the project provides a robotic control framework based on open-source software, which can be a reference for other robot control projects. The project's global planner is an innovative trajectory planning algorithm that can provide a scalable planning algorithm for other robot control projects, thus better adapting to different environments and tasks. In addition, the project can also inspire other robot control projects, especially quadruped robot control projects, to explore more advanced control algorithms and technologies, such as random distribution interactive system prediction control, reinforcement learning control. These algorithms and technologies can help robots better adapt to complex environments and tasks, improve their motion-control capabilities, and promote the continuous development and application of robot technology, providing greater convenience and benefits to society.

E. SUMMARY AND SUGGESTIONS

In the field of multilegged robots, an active compliance control method has been demonstrated to effectively improve the smoothness and stability of a robot's motion. This method also demonstrated good control performance under suspension, climbing, and other exceptional circumstances. However, certain limitations and problems associated with applying active compliance-control methods remain:

1) Robot structure design: Multilegged robot structures are complex and challenging to design, which affects the scope and practicality of this method.
2) Control precision: The motion of multilegged robots requires high precision; therefore, the Active Compliance Control method requires more refined control algorithms and parameter settings to improve control precision.
3) External environmental limitations: The application scenarios of multilegged robots are usually harsh and have various external environmental limitations, such as slopes and steep terrains. Therefore, it is necessary to consider the stability and mechanical characteristics of a robot while strengthening its motion monitoring and control.

Several improvement plans and research directions have been proposed to enhance the application of the active compliance control method and to overcome its limitations:

1) Improve the robot's structural design and manufacturing technology, optimize the mechanism design, reduce manufacturing costs, and improve the structural strength and stability.
2) Develop more refined control algorithms and parameter settings, enhance control precision, provide timely feedback on robot status information during the control process, and further improve the smoothness and stability of the robot during motion.
3) Study the interaction between the robot and the external environment, design corresponding control strategies, and develop algorithms to achieve stable motion in various complex environments.
4) The Active Compliance Control (ACC) method has the potential for further exploration in intelligent manufacturing, healthcare, and other fields. In-depth research can enrich the scope and implementation of this method. Additionally, the study of autonomous learning and adaptive control methods for multilegged robots, with the aid of artificial intelligence, the Internet, and other technologies, can provide technical support for the further development and application of ACC.

Furthermore, the difficulties of active compliance control at present are as follows:

1) How can the interaction force between the robot and the environment be obtained? However, as previously mentioned, the current loop of the detection motor can be used to estimate the contact force or use a force sensor to measure the contact force. However, the accuracy of the contact force obtained by current-loop detection is poor. Installing expensive testing equipment on a robot body increases research and development costs.
2) A multilegged robot usually installs force-sensing equipment on its leg because force-sensing equipment is a more sophisticated component, which leads to problems such as damage to the equipment during the movement process. Therefore, obtaining external force information with high accuracy and low noise limits the application of compliance control in robots.

Based on the typical research status of robot compliance control, this paper summarizes the following aspects of intelligent robot compliance control:

1) The problem of the force-position combination of gait: From the existing literature, the impedance control of the multilegged robot's foot force and position is minor and not in-depth. Therefore, contact processing, such as polishing, pressure laying, medical microsurgery, and polishing force position feedback, can be used to optimize the force-position control effect of the multilegged robot.
2) Intelligent control problem of gait force position control: With the development of depth, reinforcement, transfer, and integrated learning in the past five years, there have been few intellectual achievements in applying this type of intelligent optimization learning algorithm to improve force position control; therefore, this is a cutting-edge direction of force position control.
3) Shape control of foot force distribution: Considering the terrain estimation and foot-ground effect, there are few studies on reducing foot internal force loss and the active perception of foot force distribution feedback by multilegged robots. Therefore, it is impossible to guarantee the walking compliance efficiency of a robot under complex variable-stiffness road conditions.

The analysis showed that motion planning, force perception, and active compliance control significantly affect the movement of multilegged robots. However, there are new considerations in these areas, such as the force-position combination problem of gait, intelligent control problem of gait force position control, and shape control problem of foot force distribution. Our proposed solution to this problem is to integrate reinforcement learning and an output probability density function intelligent learning control strategy. In addition to human perception, motion planning, active compliant control, stability, and self-learning are indispensable in multilegged robots' smooth and flexible walking on complex unstructured ground. Quadruped robots serve as an example for reviewing the research, development, and problems of multilegged robot stability and reinforcement learning.

IV. GAIT STABILITY AND DEEP REINFORCEMENT LEARNING FOR QUADRUPED ROBOT

The stability of a multilegged robot refers to its ability to maintain equilibrium and restore it after a transition period such as walking. Static or dynamic stability is often used as a discriminant index for the stability of multilegged robots. Static stability refers to the ability of a robot system to return to its original stable operation after a minor disturbance occurs and the running state of the system changes. Dynamic stability refers to the ability of a robot to maintain a long

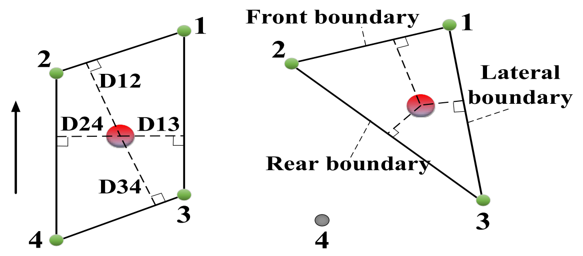

FIGURE 19. Stability margin.

process and operate stably after a significant disturbance in the system [107].

A. STABILITY CRITERION OF THE ROBOT

1) STATIC STABILITY CRITERION

It is a performance index that remains stable on a constant plane, including static, stable, and stable energy boundaries. In 1968, McGhee et al. proposed the concept of a robot stability margin at the University of Southern California, which was defined as the minimum distance from the vertical projection point of the robot's center of gravity to each side of the foothold triangle. It was used to analyze and evaluate the stability of the robot on the horizontal plane [109], as shown in Fig. 19.

In 1979, McGhee et al.proposed the static, stable boundary method (SSM). This method uses the projection and position relationship of the center of mass in the support plane to determine whether the robot is stable. However, this method only considers the position and centroid distribution of the fuselage and does not consider the displacement and acceleration caused by the robot's force [110].

In 1985, Messuri et al.from General Motors Corporation introduced the concept of Energy Stability Margin (ESM) as a function of the robot's center of gravity height, the vertical distance from the center of gravity to the supporting edge, and the mass of the robot. However, this method is limited because it only considers the gravitational potential energy of the robot and does not consider the inclination of the support surface. It does not consider the kinetic energy of the robot system or the effects of external disturbances [111]. To solve these problems, Hirose standardized ESM and proposed the Normalized Energy-Stable boundary Method (NESM) [112].

In 1987, Song et al. defined the Longitudinal Stability Margin (LSM). The minimum distance from the projection of the center of gravity along the longitudinal direction to the front boundary (front boundary) and back boundary (rear boundary) of the supporting polygon is defined as the longitudinal stability margin of the robot [113]. The following is a summary of the usage scenarios for the static-stability criterion. The application scenarios for the classical static stability criterion are summarized in Table 6.

Static stability is a crucial performance metric to ensure the robot's position and balance on a horizontal surface. Numerous methods have been proposed to assess the static stability of robots, including robot stability margin, static stable boundary method, energy stability margin, and longitudinal stability margin. These methods consider various factors, such as the center of gravity, support polygon, and the potential and kinetic energy of the robot. They are helpful in various applications, such as robot design and control. However, each method has limitations, and researchers should strive to improve its accuracy and usefulness. In the following section, we discuss the dynamic stability criterion and relevant scenarios in the system.

TABLE 6. Static stability criterion.

Method	Applicable scenarios
Center of gravity projection method	flat ground
Static stability boundary method	sloping land
Longitudinal Stability Boundary Method	sloping land
Energy Stability Boundary Method	sloping land
Normalized energy stability boundary method	flat ground

2) DYNAMIC STABILITY CRITERION

The development of robots for dynamic stability is slower than that for static stability. Furthermore, most methods for dynamic stability are based on static stability criteria. Therefore, the dynamic stability criterion can assess a robot's static and dynamic stability under specific conditions [114], including the zero-moment point, pressure center, and force-angle methods.

Papadopoulos et al. proposed the concept of a wrestling stability margin. This method determines the robot's stability based on the angle between the action line of the centroid and the vertical line (from the centroid to the boundary of the robot support polygon) [115]. In 1972, Vukobratović and Stokć, a Yugoslav scholar at the Mihailo Pupin Institute for Automation and Telecommunications, proposed the zero-point moment method [116]. This method holds that if gravity, external force, and inertial force exist on the ground, then the resultant moment of a point is zero. This point is called the ZMP. The robot was stable if the ZMP was in the support area. The formula is shown in Eq. (9):

Lin and Song presented a method for calculating the Dynamic Stability Margin of a quadruped margin (DSM) [117]. Yoneda and Hirose proposed a stability determination method called Tumble Stability [118]. Won M defined the basis for determining the stability of a quadrupedal robot using trot gait, called the Landing performance Ratio (LAR) [119].

$$\begin{cases} X_{zmp} = \dfrac{\sum_{i=0}^{n} m_i \left(\ddot{Z}_i + g_z\right) X_i - \sum_{i=0}^{n} m_i \left(\ddot{X}_i + g_X\right) Z_i}{\sum_{i=0}^{n} m_i \left(\ddot{Z}_i + g_z\right)} \\ Y_{zmp} = \dfrac{\sum_{i=0}^{n} \left(\ddot{Z}_i + g_z\right) Y_i - \sum_{i=0}^{n} m_i \left(Y_i + g_Y\right) Z_i}{\sum_{i=0}^{n} m_i \left(Z_i + g_z\right)} \end{cases} \tag{9}$$

where m_i is the mass of each component; X_i, Y_i, Z_i is the, X, Y, and Z coordinates of the center of mass for each element; and g_z is the acceleration of gravity.

In 2005, Li et al. improved the stability and anti-tipping ability of a system by changing its configuration and proposed the stable cone method [120]. The tipping performance index was used to comprehensively evaluate the static and dynamic stabilities of the mobile robot. In 2008, Meek et al. analyzed the stability of a quadrupedal robot and proposed an increase in stability by reducing the pitching motion of the robot [121]. In 2009, Sandra Nauwelaerts proposed that quadruped vertebrates produce periodic lateral and longitudinal spinal shifts during exercise. This contribution can improve the distance between the ZMP point and the foot end of the body [122]. In 2010, Kalakrishnan et al. generated a quadruped gait by planning the ZMP trajectory, realizing fast movement on rugged terrain [123]. In 2013, Lee and Park [124] proposed a natural trajectory center point control and a variable impedance control method to verify the motion stability and performance of the control method. In 2015, Wang et al. analyzed the robot's stability using the ZMP theory. They proposed a method for determining the optimal stable point in a suboptimal support triangle ZMP [125]. This contribution can control the torso posture in a stable range and use improved zero-impact foot trajectory planning to realize continuous and stable gait walking on a slope.

In 2016, Han et al. analyzed the slope motion stability of a quadrupedal robot based on the distance between the landing point of the robot centroid on the slope and the support line. They determined the value of attitude adjustment [126]. The simulation results demonstrated that the proposed attitude adjustment strategy effectively improved the slope motion stability of the quadrupedal robot. In 2017, Ma et al. proposed a method for adjusting the centroid of the slope by varying the length of the foreleg calf, while keeping the length of the hind leg calf unchanged [127]. The simulation results demonstrate that the proposed centroid adjustment method can realize the stable walking of the robot on a 20 °slope. In 2018, based on ZMP theory, Ma et al. proposed a quadrupedal robot to adjust the centroid position by adjusting the length of its front and rear legs [128]. The simulation results demonstrated that the pitch angle of the quadrupedal robot fluctuated slightly during motion. In 2020, Ma et al. proposed an adjustment method with slope motion attitude for a quadrupedal robot with a flexible spine [129]. We analyzed the influence of the degree of spine bending on the body attitude and conducted static and dynamic stability analyses of the robot slope. The effectiveness of the proposed method is verified through simulations. Table 7 summarizes the most common dynamic stability criteria and their application scenarios.

The development of dynamic stability in robots is slower than that of static stability. Several methods have been proposed to address this issue, including the zero-moment point, pressure center, and force-angle methods. Additionally, various innovative methods such as the stable cone method, landing accordance ratio, and tumble stability have been proposed

TABLE 7. Dynamic stability criterion.

method	Applicable scenarios
Zero Moment Point (ZMP)	Flat and sloped ground
center method	no clear suitable scenario
angle method	Flat and sloped ground
Poincaré-Lyapunov theory	no clear suitable scenario

to calculate the dynamic stability margin of quadrupedal robots and determine their stability. Moreover, researchers have suggested adjusting the centroid position or varying the lengths of quadrupedal robots' front and rear legs to improve slope stability. Overall, these methods enhance robots' static and dynamic stability and enable them to perform various complex tasks in diverse environments.

The reviewed articles and studies indicate that the traditional stability criteria for multilegged robots have significant limitations when dealing with complex environments, such as sand, gravel roads, variable slopes, and high-speed gaits, such as running and jumping. Artificial intelligence can autonomously process complex information and optimize decision-making and control. To address the complexity and uncertainty of the motion environment and tasks of multilegged robots, researchers have introduced artificial intelligence methods into their motion control systems of multilegged robots. Using human-simulated intelligent control decisions, a control system was developed in the desired direction, thereby achieving the intelligence of a multilegged robot system. This study presents modern control methods for robots that effectively address this issue.

B. APPLICATION OF DEEP REINFORCEMENT LEARNING TO CONTROL QUADRUPED ROBOT

Reinforcement learning involves interactions between agents and their environment. The agent interacts with the environment and receives cumulative rewards by observing the consequences of its action. This interactive behavior is a type of trial-and-error behavior that originates from behaviorist psychology, and is a crucial foundation of reinforcement learning. Another primary basis for providing mathematical forms for reinforcement learning is optimal control [130].

The "optimal control" was first used in the late 1950s to describe the problem of designing controllers to minimize or maximize the time-varying behavior of dynamic systems. By extension, Bellman used the state and value functions of dynamic systems or the concept of "optimal return function" to define functional equations (Bellman equation) [131]. The optimal control problem is solved using a dynamic programming equation. We used the dynamic programming theory to standardize the reinforcement learning problem. Specifically, this is the optimal control of an incompletely known Markov decision process. The basic concepts of the Markov Decision Process (MDP) include perception, action, and goal, as shown in Fig. 20.

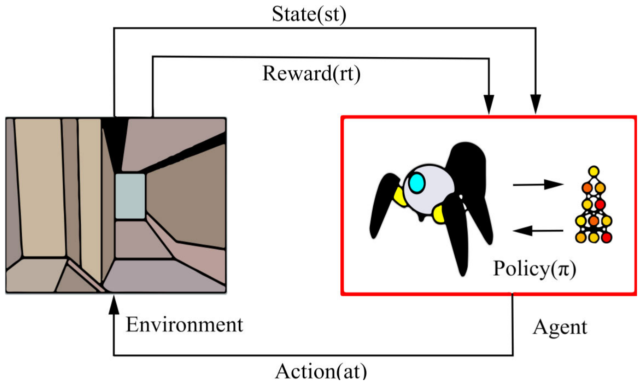

FIGURE 20. Markov decision.

At present, Deep Reinforcement Learning (DRL) [132], [133] has been widely used in games, robot control [134], [135], parameter optimization [137], machine vision, and other fields [138] and is considered a meaningful way to move towards artificial intelligence. Table 8 presents a comparison of the primary algorithms.

Standard gait control approaches for four-legged robots often require separating tasks such as contact point selection, trajectory optimization, and action space control into modules incompatible with different robot control models. Furthermore, the majority of the control modules for the same robot must be reconfigured for different task environments. Applying deep reinforcement learning can enable robots to adapt to new environments without precise modeling, thereby avoiding the complexities of controller design and parameter debugging associated with the traditional modular robot control methods.

The use of deep reinforcement learning in the control of four-legged robot gaits offers several advantages over traditional modular control methods. One of the main advantages is that it eliminates the need for precise modeling and parameter debugging associated with controller design. Instead, the robot can learn and adapt to new environments by trial and error, which makes it more adaptable to a broader range of environments without requiring significant modifications to its control modules. Furthermore, deep reinforcement learning allows for integrating multiple tasks into a single control module, enabling robots to perform complex maneuvers with greater efficiency and accuracy. This is because the robot learns to optimize its movements based on its interactions with the environment rather than relying on pre-programmed control modules that may not be suitable for all situations. Applying deep reinforcement learning represents a promising four-legged robot gait control approach, potentially improving adaptability, performance, and versatility.

In 2018, Peng et al.used the Proximal Policy Optimization (PPO) algorithm to simulate and train the Cheetah model to walk, run, jump, and flip [139]. Its main contribution is to verify the importance of the early termination of training. In 2018, Tan and Zhang realized the movement of the Tort and Gallop gaits of quadruped robots using deep reinforcement learning, improved the robustness of the measurement and control strategy by reducing the observation space and successfully transplanted simulation training into a natural environment [140]. In 2019, Jemin and Lee of the Federal College of Zurich proposed a neural network training transplant method that increased the movement speed of ANYmal by 25% and provided a more effective anti-fall ability [141]. In 2020, Athanasios of the Athens Institute of Technology combined deep reinforcement learning with foot trajectory planning to achieve 15 slope-stable motions in a Laelap II robot [142], as shown in Fig. 21.

In 2021, Kim et al. used Q-learning to determine the optimal motion contour of the spinal joint and used the motion contour of the spinal joint to achieve a boundary gait in a robotic system [143]. Although the motion contour obtained using Q-learning did not wholly match the spinal angle of the cats, the actual trend of the spinal motion contour was sinusoidal. In 2021, Atar et al. proposed a type of automatic learning control for a pneumatic quadrupedal robot that realized minimum adjustment and attempted to learn the neural network, resulting in a jumping gait. The development of this method makes the resulting gait more robust when faced with unexpected environmental changes [144]. According to this project, interested parties can optimize the reinforcement learning process for other types of gait and terrain to enhance robustness. In 2022, Shao et al. proposed a framework for using the close correlation between robot motion and gait generation to train a simple control strategy for quadruped robots to move with various gaits [145]. According to this scheme, a more advanced gait generator design can narrow the gap between the robot, legs, and animals. In 2022, Zhu et al. proposed a new collision avoidance system that allows robots to collaborate with human operators in unstructured and complex contexts [146]. In future studies, researchers could combine other technologies, such as the Kalman filter and recurrent neural networks, to further improve the effectiveness of robots in the face of movable impediments. In 2022, Castillo et al. proposed a new Reinforcement Learning (RL) framework to design a cascade feedback control strategy for three-dimensional biped motion. The algorithm concurrently tackles two significant difficulties in biped motion: trajectory planning and feedback correction [147].

In contrast to the previous RL approach, this technique breaks the biped walking problem into two modules: physical insights from the nature of walking dynamics, and a mature hybrid zero-dynamics solution for 3D biped walking. In 2022, Bellman demonstrated the most recent advancements in machine learning algorithms and libraries, which enabled robots to learn to walk on all fours in less than 20 min when combined with finely tuned robot control [131]. This study encouraged robotics research in the real world.

In unstructured environments, foot contact information for the steady motion of a multilegged robot is randomly distributed. Deep Reinforcement Learning (DRL) is a promising learning strategy for uncontrolled environments that do not require domain knowledge. It positively

TABLE 8. Comparison of the main algorithm.

research target	name	advantages	disadvantages	Scope of application
To solve algorithm convergence problem in high dimensional state action space task	Based on the value function algorithm	Slight variance & good convergence	Poor convergence	Solve high dimensional or continuous state space tasks
	Strategy gradient algorithm	good convergence	Significant variance & easy to fall into the suboptimal solution	
Solve the problem of improving algorithm sample efficiency in complex application scenarios	off-policy	Low sample complexity & good exploration performance	Significant variance & slow convergence	Suitable for complex modeling tasks.
	on-policy	High sample efficiency & strong generalization ability	Implementation complexity & limitations	It is suitable for simple modeling, especially for tasks with dynamic equations
Solve the algorithm exploration problem in the case of sparse or hard-to-define reward function	Internal reward method	Implement a simple	Susceptible to environmental noise interference	Suitable for solving simple tasks that do not require sequential reasoning
	Layered reinforcement learning	The algorithm has strong robustness	Implementation complexity & requires a design hierarchy	Suitable for solving complex tasks with sparse reward functions
	Reverse reinforcement learning	Be able to learn the appropriate reward function directly from expert experience	High sampling cost	For tasks where the reward function is difficult to define
Solve the problem of algorithm generalization ability enhancement in multi-task scenario	Methods of multi-task reinforcement learning	The generalization effect is suitable for different tasks	The complexity of the model structure is proportional to the number of training tasks	This method is recommended when a large number of task samples are required
	Meta-RL methods	Low requirements for data volume	Poor generalization effect & complex algorithm	This method applies to scenarios with a small number of task samples

impacts a multilegged robot's motion reinforcement learning algorithm in unstructured environments. Unfortunately, the DRL algorithm is primarily used in simulated environments because of the imperfections in the samples.

C. TYPICAL EXAMPLE OF OPEN-SOURCE ROBOT'S SMOOTH MOTION

1) BAIDU'S REINFORCEMENT LEARNING ROBOTS

In 2022, Baidu's reinforcement learning team joined the robot team to propose an algorithm based on a self-evolving gait generator to guide reinforcement learning training. Robots can explore reasonable gaits and cross various high-difficulty scenarios through autonomous learning. Baidu has open-sourced all simulation environments and training codes and published relevant papers [136].

In order to intuitively understand the quadruped robot and its crossing performance, its model and crossing scene diagram are shown in Fig. 22. Their approach outperforms previous learning-based proposals in challenging simulation tasks such as balance beam walking and plank jumping. They showcase the potential of their framework for real-world tasks by transferring the controller to a 12-DoF quadrupedal robot using sim-to-real transferring. Their contributions include optimizing foot trajectories and a learning-based approach for quadrupedal locomotion that alternates trajectory generator optimization via ES and neural network policy optimization via RL. They successfully apply the controller to challenging tasks like climbing stairs and walking on a balance beam.

Before interpreting, let us review the three mainstream quadruped control algorithms at present:

1) The first direction is the open-loop gait generator, which plans the walking trajectory of each leg in advance and periodically outputs control signals to drive the robot to walk. This method allows experts to design the walking

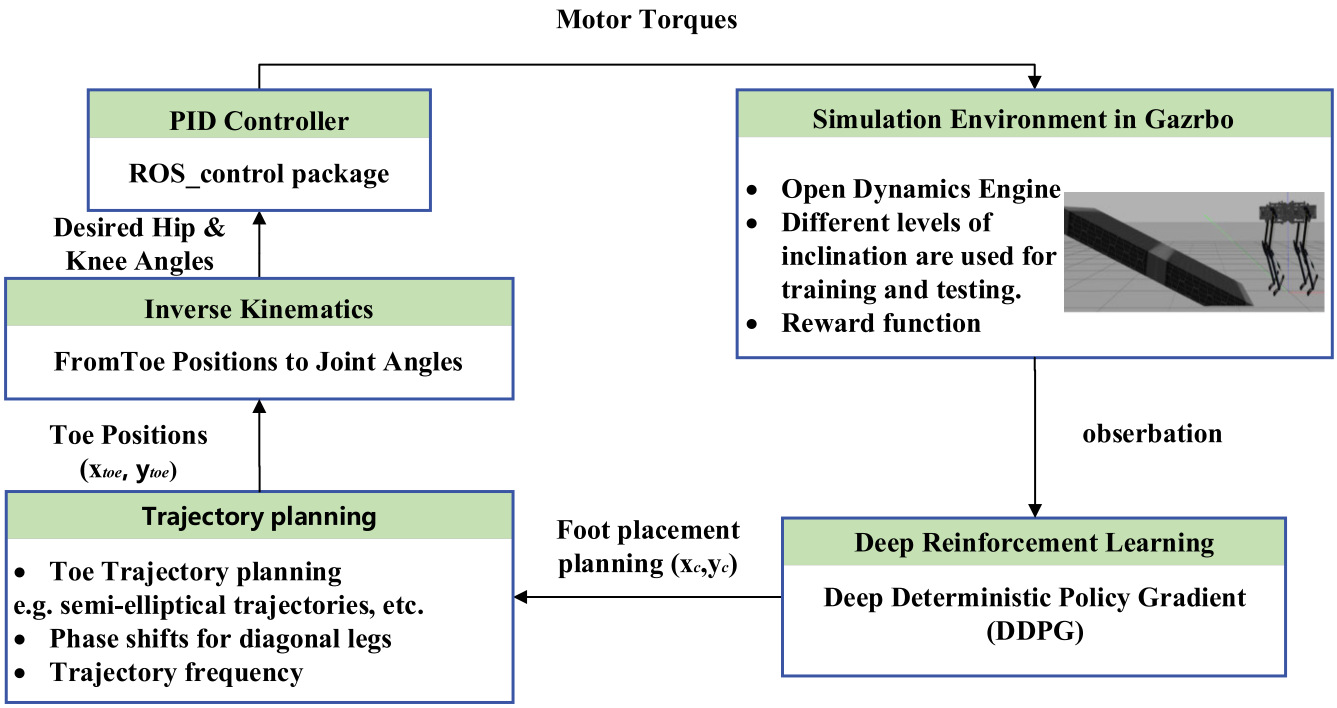

FIGURE 21. Reinforcement learning and quadruped robot motion.

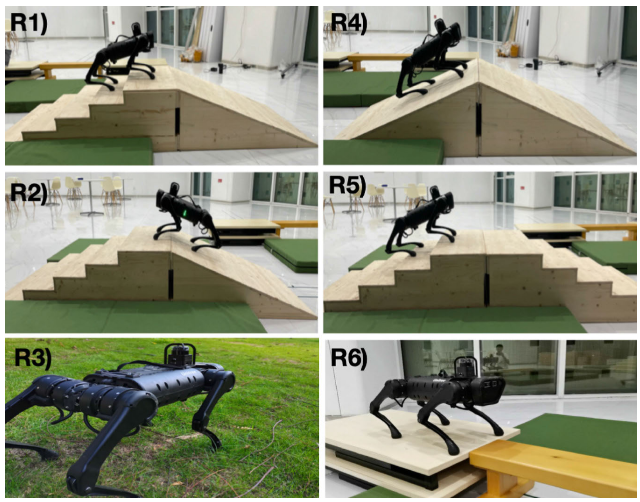

FIGURE 22. (R1) StairStair. (R2) SlopeStair. (R3) Terrain: Walking across uneven terrain. (R4) SlopeSlope. (R5) StairSlope. (R6) Balance [136].

method of quadruped robots based on experience and the actual environment, but the disadvantage is that it often requires much debugging time and expert knowledge in the field.

2) The second direction is the Model Predictive Control algorithm (MPC), the main algorithm open-sourced by MIT before. After modeling the environment, the algorithm solves the optimization problem at each time step to find the optimal control signal. The problem with this method is that its effectiveness depends on the accuracy of the environmental model, and it requires a relatively large amount of computing power to solve the optimal control signal in the actual deployment process.

3) The third direction is the learning-based control algorithm. Most previous methods designed the controller in advance and deployed it directly to the robot, without reflecting the robot's autonomous learning process. Most of the work in this direction is based on machine autonomous learning, adjusting the parameters in the machine learning model by collecting the performance data of the robot in the environment, in order to better control the quadruped robot to complete the task.

Baidu's work this time includes using reinforcement learning to train a self-evolving gait generator, which enables the robot to explore and discover new gaits that are more suitable for its environment. Reinforcement learning applied in the field of quadruped robots is not a new technology, but most of the previous reinforcement learning works can only cross some relatively simple scenarios, and do not perform well in high-difficulty scenarios, such as passing through a balance beam or jumping over obstacles. The main reason is that the complex nonlinear control system in quadruped robots makes it difficult for reinforcement learning to explore, and the robot often falls after only a few steps, making it challenging to learn effective gaits from scratch.

2) BAIDU'S ETG-RL CONTROLLER FRAMEWORK

In order to solve the problems encountered by reinforcement learning in quadruped control, the Baidu team proposed for

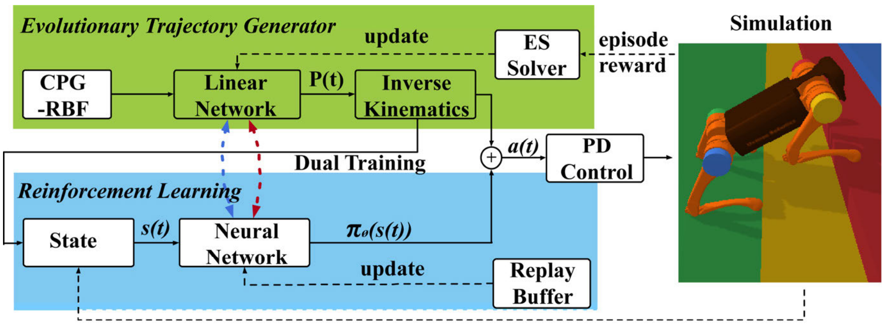

FIGURE 23. ETG-RL in simulation.

the first time a reinforcement learning framework based on a self-evolving gait generator. as shown in Fig. 23 [136].

The ETG-RL framework is an advanced robot control algorithm that uses reinforcement learning and gait generator methods to enable robots to walk autonomously in various environments. The control signal of this framework consists of two parts, the open-loop gait generator, and the neural network based on reinforcement learning. The gait generator optimizes itself directly in the trajectory space, which is more efficient than searching in the parameter space. This method can adapt specifically to the environment and improve the robot's adaptability and flexibility.

The reinforcement learning part requires outputting reasonable control signals to obtain higher rewards. The framework uses alternate training to improve training stability and efficiency during updating. The framework also reuses evolutionary algorithms to optimize the data of the gait generator and adds it to the training data of reinforcement learning to improve the effective utilization of samples. This method can reduce the number of samples required for training, thereby reducing training costs. Overall, the ETG-RL framework is an innovative combination of gait generator and reinforcement learning, achieving more efficient and flexible robot control.

3) TRAINING CURVES OF ETG-RL AND THE BASELINE METHODS ON SIMULATION TASKS

Baidu developed nine experimental scenarios utilizing the open-source pybullet software, which consisted of stair climbing, slope, and barrier-jumping tasks. The novel algorithm proposed by Baidu exhibited superior performance compared to traditional open-loop controllers and reinforcement learning algorithms. According to experimental findings, Baidu's innovative framework (indicated by the green line) surpassed all other algorithms and was the sole method to fulfill all designated tasks. Fig. 24 [136] depicts a graphical representation of the results obtained from the experimental section.

Baidu's study found that the ETG-RL algorithm outperforms other methods in solving all tasks and reduces the likelihood of robot falls in terrain environments. In contrast, other algorithms, such as CPG-RBF and SAC, struggle with traversing uneven environments. Using ETG for motion guidance allows neural network policies to learn effective gaits through RL.

Baidu's work demonstrates that the ETG-RL method can ultimately surpass classical algorithms in quadruped robot control and may become an opportunity for reinforcement learning and evolutionary learning to start large-scale landing and practical application in complex nonlinear systems. The model and training method are synchronously open-sourced in the PaddleRobotics robotic algorithm library and the PARL reinforcement learning framework; the quadruped robot and complex terrain simulation are also open in the 'rlschool' reinforcement learning environment set of Paddle, which facilitates more experts and engineers in this field for comparative research.

D. SUMMARY AND SUGGESTIONS

Gait stability and deep reinforcement learning are emerging research directions that explore machine-learning methods to achieve more stable gaits for quadruped robots. However, these methods have certain limitations that must be addressed. First, the existing methods rely mainly on deep reinforcement learning algorithms, which require large amounts of training data and computational resources. This results in long training times, high computational costs, and models prone to overfitting. Therefore, it is necessary to improve the training and generalization abilities of the algorithm. Second, the stability of quadrupedal robots is affected by multiple factors such as uneven terrain, wind, and load. Existing methods often consider only a single factor, which is insufficient for ensuring the stability of quadrupedal robots in complex environments. Therefore, it is necessary to carefully consider the effects of multiple factors on the stability of quadrupedal robots. To address these issues, improvements and explorations can be made in the following areas:

1) Optimizing the algorithm structure: More efficient algorithm structures, such as combining deep reinforcement learning and transfer learning, can be explored to reduce the training time and computational costs and improve the model's generalization ability.

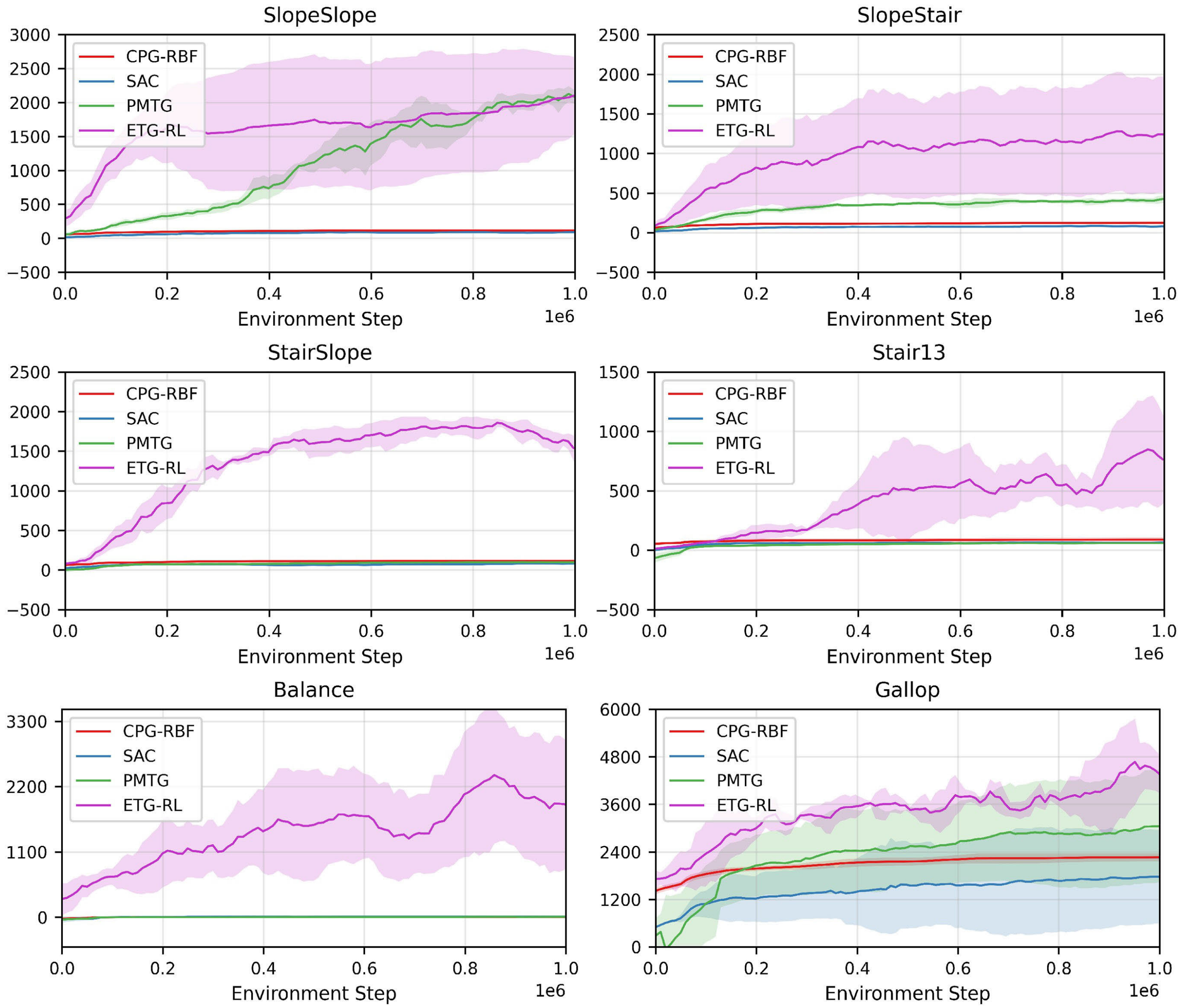

FIGURE 24. Training curves of ETG-RL and the baseline methods on simulation tasks.

2) Considering multiple factors: By establishing a more detailed environmental model, multiple factors, such as terrain, wind, and load, can be comprehensively considered for their impact on the stability of quadrupedal robots. Simultaneously, multiple sensors were used to collect comprehensive environmental data.
3) Physical simulation methods can be combined with physical simulations to verify the algorithm's effectiveness in establishing stability models for quadrupedal robots in different environments. Simultaneously, the physical simulation results can help optimize the parameters of the learning algorithm and improve the model's performance and generalization ability.
4) A combination of deep reinforcement learning and traditional control methods: A combination of deep reinforcement learning and traditional control methods can be explored to fully leverage the strengths and improve the stability and motion ability of quadrupedal robots.

DRL is a weakly supervised learning method involving interacting with the environment. It combines the advantages of modern depth perception and traditional reinforcement learning decision-making ability, and has the characteristics of data-driven and autonomous learning. This method has a strong generalization ability and can ensure a quadrupedal robot's more efficient and superior motion performance. However, the deep reinforcement learning method does not require manual intervention and regulation; therefore, some difficulties in robot control differ from traditional control methods, such as an extended learning time and quick suboptimal strategy:

1) Given that the study time is too long, this study proposes the following:

a. A cluster of computing units with substantial computing power is used to perform distributed computing. Different data types are input into other computing units to improve operational efficiency.
b. We can Increase the professional data acquisition feedforward and screen the initial model data (for example, a quadrupedal robot can add an MPC control method for preliminary data screening in the initial stage of learning to reduce the useless data of the model in the initial stage of learning and speed up learning efficiency).

2) This study recommends the following to solve the model learning problem, which often employs a suboptimal strategy:

a. At the model construction level, different training and evaluation networks are constructed to reduce the similarity of the model in learning.
b. In the experience playback pool of continuous action space algorithms, such as Deep Deterministic Policy Gradient (DDPG) and Actor–Critic (AC), random data sampling is enhanced, and data correlation is reduced.
c. For quadrupedal robot control, an offline strategy was adopted to strengthen the Ape-X algorithm, which could fully explore the environment.

In summary, gait stability and deep reinforcement learning for quadrupedal robots are promising research topics. Continuous exploration and improvement can provide more effective solutions to improve quadrupedal robots' stability and motion ability. Given the advantages of multilegged robots walking on unstructured, complex terrain and the random distribution characteristics of foot contact force information, this study mainly focuses on the smooth movement of multilegged robots. Here, we have summarized, analyzed, commented on, and suggested literature on the human perception and motion planning of multilegged robots, active compliance control, stability, and reinforcement learning.

Although the abovementioned research has improved the locomotion capabilities of multilegged robots to some extent, there are still some inherent issues. Some robots can only move smoothly in specific environments, whereas certain algorithms require specific mechanisms for multilegged robots. Additionally, some stability algorithms have a limited range of effectiveness, whereas others require a higher number of samples. Building on this research, we propose a novel approach that combines PDF intelligent learning and intelligent switching control to regulate the foot force and ensure gait compliance.

V. PROSPECT OF COMPLIANT GAIT OF MULTILEGGED ROBOT BASED ON PDF INTELLIGENT LEARNING CONTROL AND SWITCHING CONTROL

A. RESEARCH ON INTELLIGENT CONTROL OF COMPLIANT GAIT

In contrast to the traditional precise position control, compliance control allows for the displacement of each joint in response to external forces, thereby avoiding significant shifts in the output force resulting from slight displacement deviations. This control is beneficial for interacting with external objects, such as holding or polishing objects, and foot touchdown buffers. Passive compliance is typically achieved through mechanical deformation to comply with external forces, whereas force-based control methods achieve active compliance. Although active compliance requires a higher broadband sensor, it offers a greater control flexibility.

1) COMPLIANT CONTROL OF GAIT

The smooth walking process of a robot is significantly affected by the force it encounters from the external environment, making its control more challenging. Compliance control can be categorized as passive or active. Passive compliance control is limited in its application range because of its inability to obtain force information and fully track the necessary force. Because of the shortcomings of passive compliance control, most experts and scholars have focused on active compliance control, precisely force control. Effective control methods include stiffness, impedance, force/hybrid position, and implicit force controls. Force-impedance control and force/position hybrid control have been extensively studied among these methods. In 2016, Huazhong University of Science and Technology and Wan adopted a force-based impedance control in a robot one-leg compliance control experiment [149]. It achieves more accurate position tracking through dynamic compensation. A control block diagram is shown in Fig. 25. A comparison of the force-position compliance control methods is presented in Table 9.

Multilegged robots often experience instability in soft terrains and unknown environments due to trajectory planning errors and imbalanced foot forces. Controlling foot force is essential for achieving a compliant gait. Foot force control provides the necessary support force during the support phase to prevent sliding, reduce the internal force, minimize energy consumption, and optimize foot force distribution. This study aims to enhance the adaptability of multilegged robots to their environments. In recent years, intelligent control methods, such as adaptive control, fuzzy control [150], sliding mode control [151], and neural network control [152] have significantly enriched the research on compliance control. In addition to the literature mentioned in section III, two references have been added. So far, there are mainly two ways to combine robust control for force control: robust impedance control and robust force-position hybrid control [153]. One-leg active compliance control was designed to establish a simplified mathematical model of the hydraulic driver [154]. The output torque of the robot joint was controlled using this model. The help of a virtual model based on joint torque control realizes active compliance control of one leg. Finally, experiments conducted on a one-leg platform verify the effectiveness of the proposed method. Active compliance control of one leg was based on a virtual model. In the virtual projectile-damping model of the robot foot, the virtual force F acting on the foot is calculated to control the leg motion based on the error between the actual position of the foot pf and the given position.

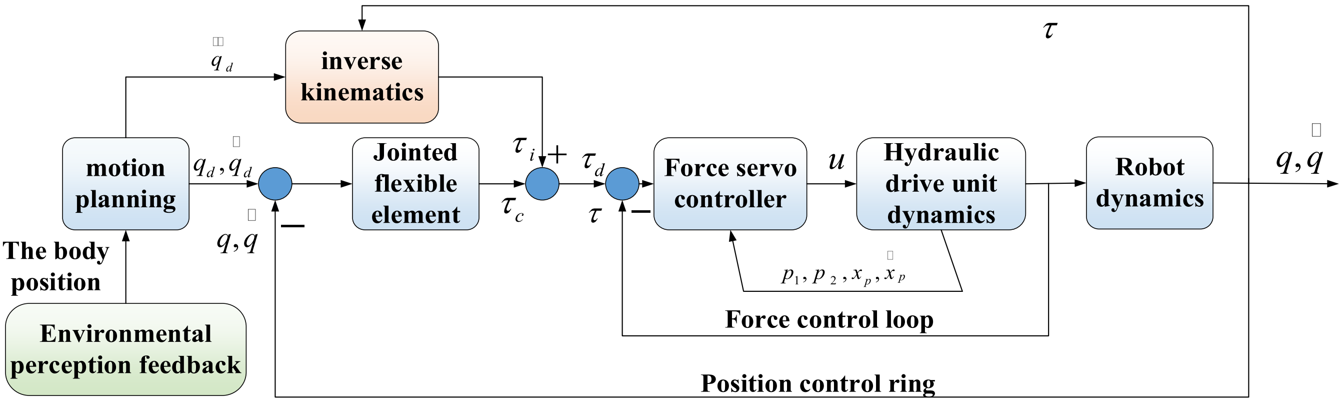

FIGURE 25. Block diagram of force-based impedance control strategy proposed by Huazhong University of Science and Technology.

TABLE 9. Comparison of force-position flexibility control method.

classification of method		workspace	Measured variable	Modified variable	Regulated object
Active rigidity control	Method 1	Joint space	Position and force	Joint offset, contact force	Joint stiffness matrix
	Method 2	Task Space		Position error, contact force	Rigid matrix
impedance control	Basic impedace control	The task space	Position, velocity, force	Position and velocity error, contact force	impedance
	Position-based impedance control			Correct desired trajectories and contact forces	
Admittance control			force	Force error	admittance
hybrid control	Hybrid force/ bit control	Position subspace	Position	position error	Position
		Force subspace	force	Force error	force
	Mixed impedance control	Position subspace	force	velocity error	Position space impedance
		Force subspace		Force error	Force space impedance
Direct force control	PI, PD, PID	The task space	force	Force error	Expect force
Interrelay control		The task space	Position	position error	Preset stiffness

The following aspects of intelligent robot compliance control are summarized based on the typical research status of robot compliance control.

a. Shape control of foot force distribution: Few studies on multilegged robots actively perceive the shape of foot force distribution when considering terrain estimation and foot-ground interaction.

Therefore, it is infeasible to guarantee the compliance efficiency of multilegged robots under complex road conditions with variable stiffness.

b. A dynamic continuous variable force distribution model can be studied using computing technology. Furthermore, intelligent learning planning and stability control can be further studied.

2) COMPLIANT SWITCHING CONTROL OF GAIT

Switched systems (SSs) are hybrid systems comprising continuous or discrete subsystems along with switching rules that coordinate these subsystems. Switching control of gait compliance is crucial for ensuring multilegged stability, adaptability, and versatility. This feature enables robots to adapt their gait to changes in the environment such as walking on different terrains, thereby enhancing their ability to navigate various scenarios. In addition, the ability to switch between

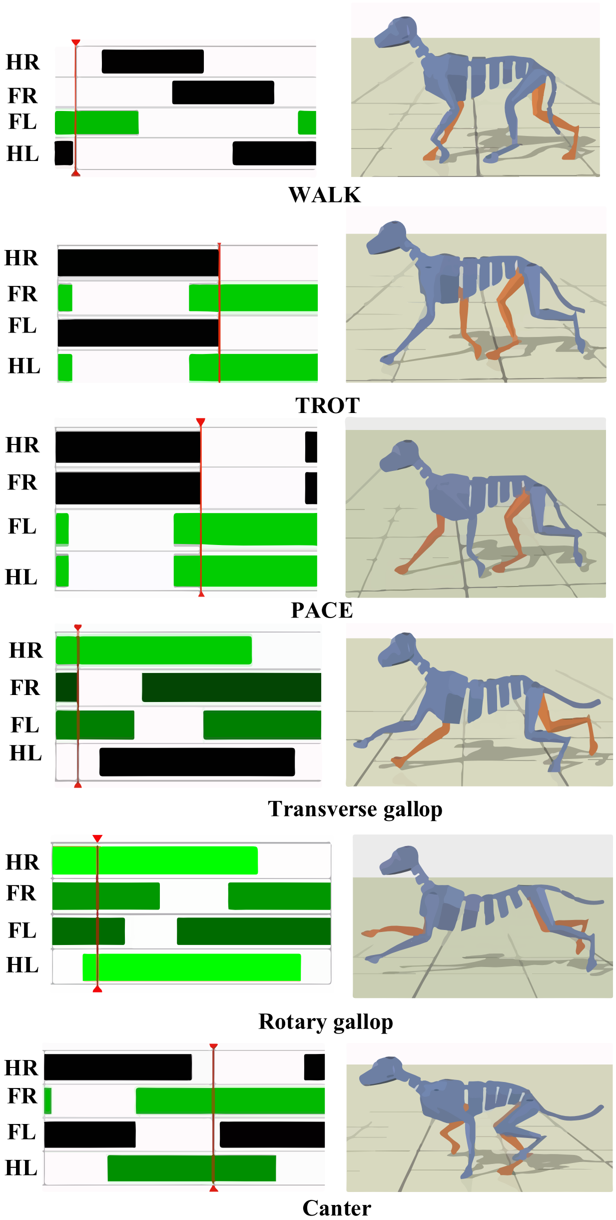

FIGURE 26. Comparison of quadruped gait.

different levels of compliance in their joints enhances the stability of these robots and reduces the likelihood of falls, thereby increasing their safety. Furthermore, gait compliance switching control can improve the energy efficiency of multilegged robots, thereby reducing their power consumption. Therefore, this concept is vital for the practicality and success of multilegged robots in various industries, including search and rescue, agriculture, and military applications. In the past ten years, research on SSs has been a hot topic discussed by scholars [155], [156]. A comparison of the various movement gaits of four-legged robot dogs [157] is shown in Fig. 26.

Theoretical research and the application of stabilization methods for nonlinear switched systems with unstable modes have established an equilibrium relationship between the stable modes, unstable modes, and jump dynamics, which is crucial for stabilization. The current trends are as follows.

a. The systems are nonlinear and have switched components with changing parameters over time.
b. Nonlinear switched systems with distributed parameters are a complex topic in control theory.
c. Ordinary differential-partial differential coupled switched system.

Research on the gait-switching control of multilegged robots focuses on quasi-static walking multilegged robots. The gait switching control method based on predictive control realizes switching of the walking step and step speed, and is widely used in soccer robot matches [158]. Based on the robust control of the simplest passive model of the discrete control Lyapunov function, a gait transformation method based on pure passive walker research was proposed [159]. With the change in walking terrain, the robot can be converted to an adaptive walking gait in a few steps, which helps develop a robust control method and adaptive walking of dynamic passive motion robots. During walking, the robot often faces external disturbances and special road conditions such as wind force, artificial traction, and gully bulges. Biped robots often need to switch their gaits to achieve relaxed walking. To address the gait switching problem of a five-bar underactuated 3D biped robot, a switching control strategy based on hierarchical control was proposed in [160]. The designed switching controller enables the robot to transition smoothly from its current gait to the target gait.

Given the typical research status of smooth motion under foot-ground force, this study aims to address the lack of theoretical research on critical technologies for motion control of multilegged robots in complex field terrains. Thus, the following problems were identified:

a. Motion planning: The basis of multilegged robot walking. Few studies have been conducted on reducing the robot's foot–ground impact force and energy consumption by optimizing the foot trajectory by aiming at a foot structure with passive elasticity.
b. The problem of state estimation and ground force distribution: Owing to the considerable noise in the output signal of the body sensor, a single sensor cannot accurately measure motion state information, such as body speed and posture. Foot-ground force distribution is difficult to measure, but few studies have estimated the multilegged motion state and foot-ground force distribution.
c. Optimization of full-force distribution: The control of the full-force distribution is essential for realizing robot control. Under the premise of considering terrain estimation and foot-ground action, there are few studies on reducing the internal force loss of multilegged robots in steady-state walking. Therefore, it is impossible to guarantee the walking efficiency of multilegged robots in complex and variable-stiffness terrain.

In summary, the existing multilegged robots oversimplify the multilegged support phase by modeling it as an instantaneous rigid collision. However, in practice, the multilegged support phase of a robot is a continuous elastic process. Future research should focus on accurately establishing a dynamic model of the constant multilegged support phase and performing gait compliance planning and stability control. The goal of gait compliance and control is to design a multilegged robot's leg and foot control law to adapt to the movement of a complex ground environment. This remains the focus of several studies. Thus far, the gait generation and control of multilegged robots have fallen short of the expected level of intelligence. Achieving a smooth movement of the multilegged robot was necessary for the final analysis in a previous study. Therefore, it is essential to control foot strength. This study introduces a probability density function distributed shape control method to study the distributed shape control of a multilegged robot foot force.

B. REINFORCEMENT LEARNING AND SWITCHING CONTROL

Obtaining an accurately controlled object model is essential, but is often challenging. The design of a nonlinear controller is complex and involves multiple constraints.

To address these difficulties, we propose using a black box model to determine whether a simple control strategy can achieve end-to-end control using external data. Deep reinforcement learning enables training model-free multilegged robots, such as quadrupedal robots, thereby making end-to-end control feasible. We provide a brief overview of reinforcement learning and gait-switching control.

Numerous researchers have extensively studied optimal planning forhuman–environment interactions. Juang proposed a method for robotic arm evolution following the control of a hexapod robot by using a new multi-objective evolutionary fuzzy control method to control a hexapod robot's walking direction and speed during a robotic arm-following task [161]. Hemminghaus and Kopp focused on robots' adaptive social behavior generation using reinforcement learning [162]. Kim and Kon proposed an effective reward function method for reinforcement learning based on classification behavior recognition [163]. Duguleana and Mogan developed an obstacle avoidance neural network for mobile robots based on reinforcement learning [164]. Lele et al. applied CPG to a hexapod robot, and the online reinforcement learning of a bionic walking gait was energy-efficient [165]. The learning process converged to the desired animally observed tripod in 70% of the cases, whereas in the other cases, it converged to a suboptimal gait that still allowed movement. One of the most complete and adequate reinforcement learning algorithms for footed robots has been proposed [166]. It is based entirely on reinforcement learning for gait-switching control of the quadrupedal robot body, as shown in Fig. 27.

This paper presents a system that offers the potential for future applications of reinforcement learning. By securing robot feedback data and actuators, complex robot controllers can be rapidly automated with minimal human intervention. This method significantly reduces the development difficulty compared to traditional model control theory approaches. In multilegged robot technology, reinforcement learning of the spike neural network and synchronous motion of the CPG system provide a breakthrough in end-to-end learning for mobile robot technology. In addition, a random weight update technique based on enhancement was proposed to train the peak CPG. Lele and Fang combined reinforcement learning based on spiking neural networks with the simultaneous motion of a system of CPGs in footed robotics, thereby providing breakthrough end-to-end learning in mobile robotics [167]. An augmented stochastic weight update-based technique was also proposed for training spiking CPGs. Hussain et al. proposed a foot robot based on a logic-labeled finite-state machine method for a functional control structure. The logic-labeled finite-state machine method proposes the design of a control system for a walking machine with a functional structure. As an example, the FSM-based method was tested using a V-REP simulation of insect robots [168].

Multilegged robots are complex systems that require precise control to achieve stable locomotion. PDF intelligent control can be used to predict multilegged robots' behavior and adjust their control parameters accordingly. Black-box models and reinforcement-learning strategies have been developed to overcome these hurdles and enable end-to-end control of robots. With minimal human intervention, deep reinforcement learning has made it feasible to train model-free multilegged robots, particularly quadrupedal robots. Switching control is also essential in multilegged robots because they often encounter different operating conditions during locomotion, such as changes in the terrain or gait. The control system improves the prediction accuracy by using different PDF models for different operating conditions, thereby ensuring stable system operation. Combining reinforcement learning with spike neural networks and the CPG system provides breakthrough end-to-end learning in mobile robotics. The proposed techniques offer prospects for future reinforcement learning applications and significantly reduce development difficulty compared to traditional control theory approaches.

Achieving stable locomotion in multilegged robots is a challenging task that demands precise control, highlighting the complexity of these systems and meeting the standards of top-tier publications. PDF intelligent control can be used to predict multilegged robots' behavior and adjust their control parameters accordingly. Reinforcement learning enables the control system of multilegged robots to adapt to changing environmental conditions such as uneven terrain or obstacles. Switching control is also essential in multilegged robots because they often encounter different operating conditions during locomotion, such as changes in the terrain or gait. The control system improves the prediction accuracy by using different PDF models for different operating conditions, thereby ensuring stable system operation. Applying PDF intelligent control in multilegged robots is an exciting research field.

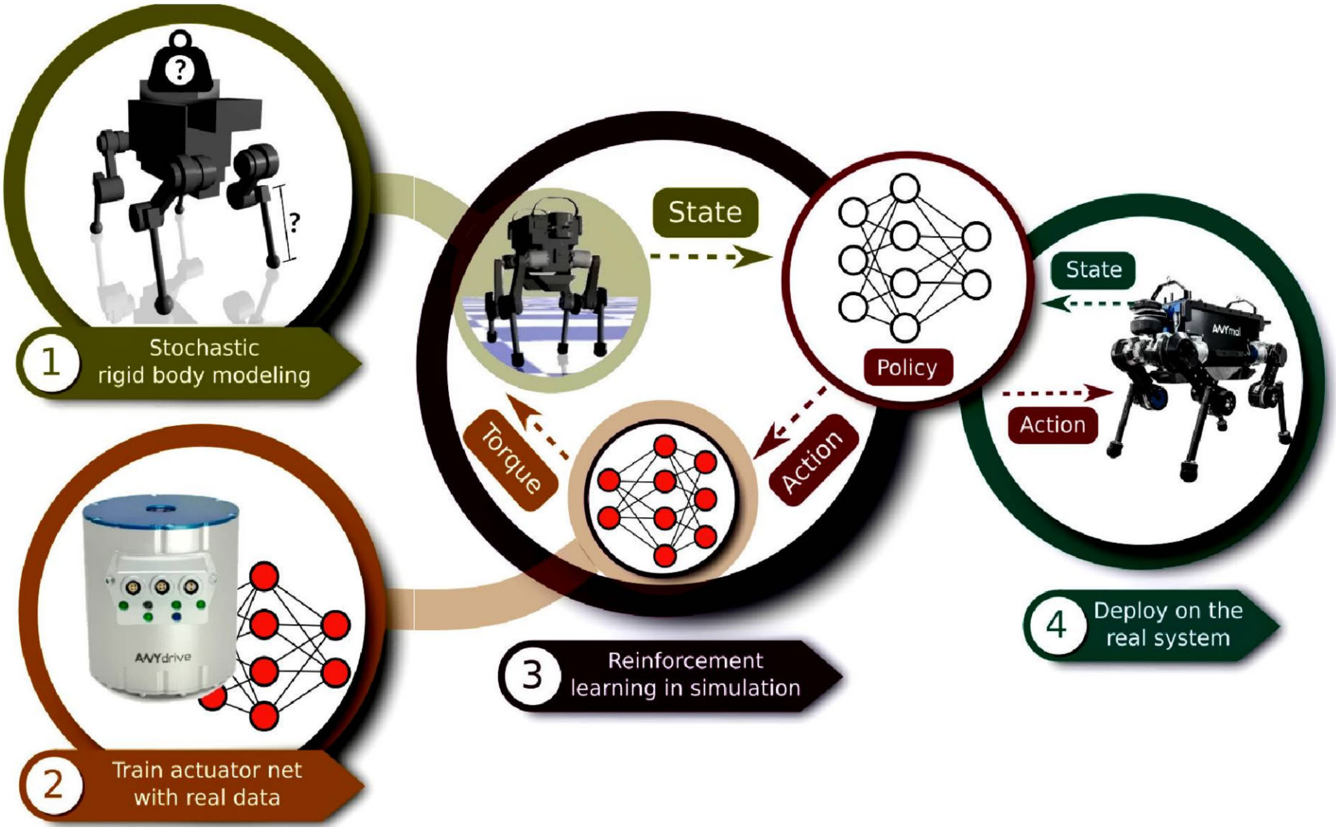

FIGURE 27. Creating a control policy.

C. THE PREDICTION OF PDF INTELLIGENT CONTROL APPLIED IN MULTILEGGED ROBOTS

PDF refers to the shape of the probability density function distribution for the papermaking process, as shown in Fig. 28). The year 2002 marked the beginning of research on controlling PDF shapes in nonlinear stochastic systems. Using the Gram-Charlier spread approximation of the expected PDF, the renowned Canadian academics Michael et al. proposed a steady-state PDF shape control method for discrete stochastic processes [169]. In 2012, a method based on the equivalent nonlinear system method for approximating the steady-state solution was proposed to design the feedback control of a nonlinear stochastic system such that the output PDF of the system tracked the target PDF [170].

In 2021, Liu et al.proposed a new control strategy for randomly distributed shape tracking for non-Gaussian nonlinear systems and discussed the joint tracking problem of multi-output stochastic systems [171]. Can this result be used to sample the foot contact force PDFs to simplify the contact collision modeling? In 2020, Xu et al.proposed a tracking technique for moving objects using a combination of linear and nonlinear motion. This algorithm causes the observation model to switch when the mobile robot switches grids [172]. Despite the lack of utilization of PDF control in legged robot motion control, the contact force information of legged robots traversing unstructured terrains exhibits characteristics of a random distribution system. The hybrid filtering method analyzed in this study provides a model for the feedback control of the contact force data of multilegged robots. In 2022, Zheng et al.proposed a control law that utilizes density estimation as a feedback signal. It generates a corresponding velocity field that directs the global distribution of robots

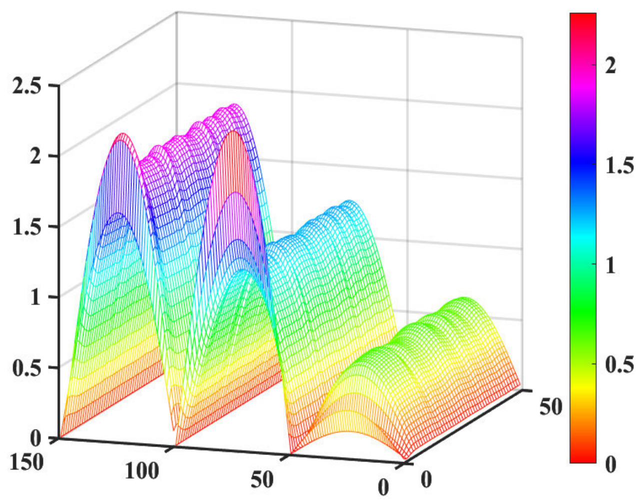

FIGURE 28. The shape of standard PDF distribution in the paper-making process.

to the desired profile by locally operating each robot. This concept bridges the divide between the local kinematics of swarm robot systems and their emergent behavior [173]. It is anticipated that probabilistic robot dynamics will be able to address distributed density-estimation problems and consider more general robot dynamics. In 2021, Zhao et al. recursively calculated the probability density function of the state of faults and states and proposed a sensor fault estimation algorithm for nonlinear state-space models. The application of this technology to robot localization and experiments on rotating flexible joints demonstrated its viability as an online sensor monitor [174]. Application of the proposed algorithm to other distributed contexts for potential enhancement or generalization must be addressed. Shi et al. proposed a novel method for surface defect recognition using CTFLCA. Specifically, this method employs only Resnet-50 ImageNet datasets for training and achieves high accuracy in recognizing surface defects in practical situations [175]. However, applying this algorithm to improve the smooth motion ability of multilegged robots utilizing PDF control remains an unresolved challenge.

This section discusses the application of probability density function control in various fields, including nonlinear stochastic systems, moving objects, and multilegged robots. This section highlights various methods proposed by researchers for controlling the PDF shape of systems, including a method based on the equivalent nonlinear system method and a new control strategy for non-Gaussian stochastic nonlinear systems. In addition, this section suggests potential applications of PDF control in simplifying the modeling of contact collisions in legged robots and the possibility of using density estimation as a feedback signal to control the global distribution of robots. Finally, the section describes a sensor fault estimation algorithm for nonlinear state-space models proposed by Zhao et al. and its application to robot localization. Overall, this section suggests that PDF control and density estimation have promising applications in various fields and are worthy of further research.

In unstructured situations, the foot contact information of a smooth-moving multilegged robot is distributed randomly. As mentioned above, leading journals have demonstrated the success of the probability density function method for robot crowds and manipulator control. However, the PDF method for unstructured environmental mobility of multilegged robots has not yet been disclosed, presenting an opportunity to fill a void. The PDF method of intelligent learning control combines traditional and artificial intelligence controls to control multilegged robots. This method accurately describes the robot's motion state and automatically learns and adjusts the controller to adapt to different environments and tasks. After effectively addressing the mobility issues of multilegged robots in unstructured environments, they will become a crucial mobile platform with fault-tolerant redundancy in various practical fields. For instance, multilegged robots integrated with artificial intelligence detectors have tremendous potential in detecting arc faults [176].

D. SUMMARY AND SUGGESTIONS

In summary, the walking process of a multilegged robot achieves flexibility in real-time gait switching by coordinating the degrees of freedom of multiple leg joints and generating appropriate leg stiffness.

Gait switching, including speed, direction, and support flexibility, has essential theoretical significance when combined with intelligent control system theory and frontier directions, such as hybrid system switching control theory, reinforcement learning, and optimal control. Innovative research on gait switching is necessary to overcome the technical difficulties of applying reinforcement learning to multilegged robots, particularly to local gait algorithms. Reinforcement learning can provide more comprehensive and reliable logic than manually designed algorithms through autonomous trial-and-error in various environments. Reinforcement learning is usually the top-level control of a robot's stability and can be integrated with traditional algorithms for switching and fusion, combining their benefits.

The two methods for smooth gait control in quadrupedal robots are PDF-based intelligent learning and switching control. PDF-based intelligent learning control uses technologies like neural networks to learn the robot's dynamic model and generate appropriate control strategies. The switching control switches different control strategies during specific gait cycles to achieve a smooth gait. However, both control methods have problems and limitations. The problems and limitations of PDF-based intelligent learning control include the following.

1) A large amount of data is required to establish a neural network model for complex robots, which is time consuming and computationally expensive.
2) Establishing neural networks requires specialized skills, which limits their applicability.
3) Adapting to changes in robots and their environments is challenging because a new situation or dataset requires establishing a new network model.

The problems and limitations of switching control include the following:

1) During gait switching, the robot is prone to instability because switching can cause the state of the robot to change abruptly before other control strategies fully adapt to the new state.
2) A robot requires considerable energy and computational resources during switching, which affects its overall performance.
3) Switching control is difficult for complex walking patterns, such as jumping.

To address the above issues, here are some improvement suggestions:

1) Deep learning techniques can reduce data requirements and run time for PDF-based intelligent learning control. Furthermore, this method can improve the accuracy and precision of neural network establishment.

2) For switching control, the gait switching process can be broken down into small steps to reduce the pressure on the robot during each step and minimize its instability.
3) PDF-based intelligent learning and switching controls can be combined, and reinforcement learning methods can overcome the data issue, directly allowing the robot and environment to interact, acquire more knowledge, and demonstrate robust adaptability.

As research on the foot-to-ground control of multilegged robots has just begun, the PDF distribution of non-Gaussian random forces has yet to be considered when studying the force-position compliance control method with random variables in the literature. Fluctuations in foot-ground contact stiffness, extreme road conditions, and gait switching of different support phases are inevitable in actual field walking. The stress change of these foot-ground contacts is exceedingly similar to the shape change of each parameter's probability density function distribution in the paper-making process. PDF intelligent learning controls blend traditional and Artificial Intelligence (AI) controls for multilegged robots. The PDF distribution of non-Gaussian random forces is yet to be explored in multilegged robot foot-to-ground control research. Therefore, we predict that drawing lessons from a control target whose output foot force is in accordance with a specific shape distribution of the probability density function can further improve the foot force control of a multilegged robot.

In this study, we analyzed smooth motion algorithms for multilegged robots, ranging from traditional control to artificial intelligence and PDF-based machine learning control. These algorithms include foot trajectory planning, motion planning, force sensing, terrain reconstruction strategies, impedance control, active compliance control, gait stability theory, and deep reinforcement-learning control. Each algorithm has its unique strengths and applications. Our PDF-based machine learning control has comprehensive advantages in force sensing, terrain reconstruction, active compliance, and adaptive learning for quadrupedal robots. However, this is only a scientific prediction based on the relevant literature. We believe that the time required to fill this gap has increased. Finally, we provide an overall discussion, summary, and outlook on the study.

VI. DISCUSSION, SUMMARY AND PROSPECT

A. DISCUSSION OF THE RESULTS

Multilegged robot motion planning is a complex research field that poses several challenges. Quadrupedal robotic locomotion requires active compliance control and gait stability. DRL and PDF intelligent learning control have demonstrated significant potential for enhancing the stability and control of multilegged robots. However, the effective implementation of these methods requires the overcoming of several challenges. Moreover, foot-to-ground control research is still nascent, and force-position compliance control studies must consider Non-Gaussian random forces. In this context, the shape change of each parameter's probability density function distribution during the paper-making process could provide valuable insights into improving the foot force control of multilegged robots.

1) Multilegged robot motion planning is a complex research field with several challenges to overcome, including real-time adaptation and control, terrain complexity, energy efficiency, and perception and sensing:
   a. Real-time adaptation and control: Multilegged robots have numerous degrees of freedom, making them versatile and challenging to control. The development of real-time adaptation and control techniques is critical to ensure autonomous operation in dynamic and uncertain environments.
   b. Terrain complexity: Although multilegged robots can navigate challenging terrains more easily than wheeled or tracked robots, they still face obstacles in complex environments. Therefore, developing algorithms for planning and executing motions on unstructured terrain is crucial.
   c. Energy efficiency: Multilegged robots consume significant energy during movement owing to their inherent complexity. Thus, designing energy-efficient control systems that optimize leg movements and overall gait is critical for achieving long-run times and increasing mission capability.
   d. Perception and sensing: Accurate senses are essential for multilegged safe and effective operations. Therefore, designing robust and dependable sensors for force, position, and orientation feedback is essential for ensuring motion stability and safety.

Despite these challenges, there are promising research prospects for multilegged robot motion planning and force-sensing technology. For instance, researchers have investigated bio-inspired motion control models that can significantly enhance adaptive capabilities. As technology advances in the coming years, significant breakthroughs are expected in these areas.

2) The active compliance control of quadrupedal robots involves designing control algorithms and hardware components that enable the robot to adjust to its environment and avoid causing damage to itself or others. The most challenging problems to overcome in this area of research are as follows:
   a. The complexity of control algorithms: Owing to the complexity of a robot's mechanical structure and the need for real-time control, developing control algorithms that can handle various degrees of freedom and robot sensors can be challenging.
   b. Integration of sensors: Several sensors must be added to the robot's control system to perceive its surroundings, and effective integration strategies for these sensors are necessary.
   c. Energy consumption: Quadruped robots require significant energy to control their joints, sensors, and actuators. Thus, reducing the energy consumption without sacrificing the performance is a significant challenge.

d. Durability and reliability: Quadruped robots are frequently used in harsh environments. Quadruped robot hardware components and control systems must be designed to withstand harsh environments, and maintenance and repair can be costly and time-consuming.

Despite these challenges, the active compliance control of quadrupedal robots has excellent research prospects owing to its potential applications in search and rescue, agriculture, and military operations. Further advances in control algorithms, sensors, energy management, and durability will likely result in increasingly practical and versatile quadrupedal robots.

3) Gait stability is a crucial aspect of the quadrupedal robotic locomotion. DRL is a powerful tool that has demonstrated significant potential in enhancing the stability of quadrupedal robots. However, several challenges must be addressed before the DRL can effectively improve the gait stability of quadrupedal robots:

a. The first problem is the model-transfer problem. DRL algorithms require a large amount of data to be collected from the robots for learning. However, collecting data from real robots can be time consuming and laborious. To address this challenge, researchers are exploring methods for transferring learned models from simulations to physical environments. This method involved training the DRL algorithm in a simulated environment and transferring the model to a physical robot.

b. The second challenge is related to the high dimensionality of state space. Quadruped robots have several degrees of freedom, resulting in high-dimensional state space. This complexity makes it challenging to design reward functions that provide meaningful feedback to the DRL algorithm. To address this challenge, researchers are exploring methods to reduce the dimensionality of the state space by using techniques such as dimensionality reduction and feature selection.

c. The third challenge is related to exploration problems. DRL algorithms require further exploration in order to develop effective policies. However, exploratory actions can be risky and potentially damaging for quadrupedal robots. Researchers are exploring methods to balance exploration and exploitation to address this challenge, such as using curriculum-based learning approaches.

Although using DRL for gait stability in quadrupedal robots holds great promise, several challenges must be addressed to obtain a practical solution. With further research and development, DRL has the potential to significantly enhance the stability of quadrupedal robots and enable them to perform complex tasks with exceptional reliability and efficiency:

a. The study of PDF intelligent-learning control-based multilegged robot-compliant gaits faces several challenges. These challenges include creating precise models of the complex dynamics of multilegged robots, designing robust and efficient learning algorithms to assist robots in adapting to diverse environments, and implementing switching mechanisms to enable seamless gait-pattern transitions. Future research should focus on several approaches to overcome these obstacles and enhance the performance of multilegged robots.

b. One possible direction is to investigate new modeling techniques that can capture the nonlinearities and uncertainties inherent in the dynamics of multilegged robots. This direction can include advanced control methods, such as adaptive and robust control, and machine learning methods, such as deep reinforcement learning.

c. An additional avenue for investigation involves the examination of practical implementations of compliant gait in realistic settings, such as search and rescue missions, exploration, and inspection of hazardous environments. These implementations may entail incorporating sensory feedback and perception systems that enhance a robot's ability to navigate and interact with its surroundings.

The development of compliant gaits for multilegged robots is a crucial and demanding research field that offers significant potential for enhancing the performance of these machines in diverse real-world situations. Ongoing research and innovation are anticipated to produce novel solutions that facilitate the efficient navigation and rapid adaptation of multilegged robots to various environments. Despite the limitations of PDF distribution for Non-Gaussian random forces, PDF intelligent learning control can potentially serve as a practical approach for controlling multilegged robots.

B. SUMMARY

The presence of multiple leg joints imbues a robot system with high complexity, nonlinearity, and strong coupling in its dynamics. To address the challenge of the smooth walking of multilegged robots on the complex unstructured ground, previous Research and Development (R&D) personnel conducted experimental and technical verifications on a single leg of the robot before applying it to the entire machine. First, we summarize and classify gait planning, foot force perception, leg movement flexibility control, quadruped stability judgment, and reinforcement learning applications of multilegged robots. Subsequently, we analyze the current control problem of the smooth movement of the robot and propose solutions.

Following an inductive analysis and summary study of the planning and control aspects involved in the smooth motion of a multi-footed robot, we propose a force control scheme to address the various random uptakes or perturbations encountered by a multi-footed robot walking on an unstructured terrain. Optimal material science and technology, flexible structural design, and stable anti-disturbance force sensors are essential for walking, robotic motion planning, and force sensing. As discussed in this study, efficient and straightforward controllers and learning control strategies are essential, particularly for model-free reinforcement learning algorithms. Consequently, future walking robots will integrate multiple technologies and research on self-learning and gait switching in ontology-environment interactions.

In summary, foot-to-ground control of multilegged robots is a nascent field with much room for improvement. Learning from PDF target distributions may improve the foot force control in multilegged robots. Integrating traditional and artificial intelligence controls, such as PDF intelligent learning control, can be a valuable method for controlling multilegged robots. Using the probability density function of Non-Gaussian random forces to improve foot force control has significant potential.

C. THE PROSPECT OF THE ROBOT'S COMPLIANT MOVEMENT

Although the active compliance control method for multilegged robots partially addresses the issue of complex passive compliance structures and single-compliance model problems, it only controls compliance from a floating fuselage or single leg. To improve their performance, multilegged robots require compliant motion control, which can be enhanced using potential technologies such as active compliance control methods and reinforcement learning.

1) Advanced Sensors such as cameras and LIDAR can be integrated into multilegged robots to offer more precise and adaptable motion control. These sensors can provide detailed terrain information and enable a robot to adjust its movement accordingly.
2) Artificial Intelligence (AI): Integrating artificial intelligence into multilegged robots can improve their ability to adapt to diverse terrains. AI algorithms can assist robots in learning how to adjust their movements and in making decisions based on the encountered terrain.
3) Soft robotics: Soft robotics is a novel field that employs soft and flexible materials for robotic constructions. Using soft materials can enable multilegged robots to adapt better to different terrains, as they can conform to the ground and adjust their movements accordingly.
4) Mimicking Biological Systems: There is another approach that can be taken to improve the compliant motion control of robots with multiple legs. For instance, researchers could examine the movement patterns of insects or other multilegged creatures to understand better how their bodies adapt to different terrain types.
5) Prosthetic-inspired Design: Prosthetics offers another approach for improving the compliant motion control of multilegged robots. Engineering prosthetics for injured animals enables experts to simulate and develop the leg structure and movement of animals, thereby enhancing the design of multilegged robots for improved motion control.
6) PDF Intelligent Control: PDF intelligent control combines traditional and AI control, and its control object is consistent with the unstructured terrain motion characteristics of multilegged robots.

In summary, these technologies present promising prospects for enhancing the motion control of multilegged robots, and we anticipate substantial progress in this field in the coming years. This study examined the challenges and prospects of investigating multilegged robots with compliant gaits. This study emphasizes the importance of motion control for multilegged robots and obstacles in attaining compliant motions on complex and unstructured terrains. This study identified the crucial factors and challenges in achieving stable motion control for multilegged robots, including foot force perception, motion planning, stability, and active compliance control. Furthermore, PDF control of foot force is proposed as a viable solution for compliant motion control in multilegged robots. Moreover, this article recognizes the shortcomings and deficiencies of current research and recommends research goals to enhance the motion control of multilegged robots.

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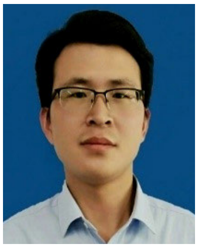

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