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Evolution, Design, and Future Trajectories on Bipedal Wheel-legged Robot: A Comprehensive Review

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ABSTRACT

This comprehensive review delves into the realm of bipedal wheel-legged robots, focusing on their design, control, and applications in assistive technology and disaster mitigation. Drawing insights from various fields such as robotics, computer science, and biomechanics, it offers a holistic understanding of these robots' stability, adaptability, and efficiency. The analysis encompasses optimization techniques, sensor integration, machine learning, and adaptive control methods, evaluating their impact on robot capabilities. Emphasizing the need for adaptable, terrain-aware control algorithms, the review explores the untapped potential of machine learning and soft robotics in enhancing performance across diverse operational scenarios. It highlights the advantages of hybrid models combining legged and wheeled mobility while stressing the importance of refining control frameworks, trajectory planning, and human-robot interactions. The concept of integrating soft and compliant mechanisms for improved adaptability and resilience is introduced. Identifying gaps in current research, the review suggests future directions for investigation in the fields of robotics and control engineering, addressing the evolution and terrain adaptability of bipedal wheel-legged robots, control, stability, and locomotion, as well as integrated sensory and perception systems, microcontrollers, cutting-edge technology, and future design and control directions.

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1. Introduction

There is a growing demand for ground mobile assistive systems that can operate in challenging environments like islands and mountainous landscapes. These environments present unique obstacles that require advanced mobile system solutions to ensure effective mobility. Bipedal walking robot is one of the legged robot mechanisms that fall into ground mobile robot family have gained significant attention. Due to its flexibility and dynamic stability, this kind of robot has potential to be enhanced in both indoor and outdoor application that exploration and human assistance throughout the uneven and confined area. These robots aim to replicate the human-liked locomotion that typically consist of two legs and strive to imitate the natural gait patterns observed in humans and other mammals [1]. Therefore, to achieve a stable locomotion, these robots require advanced control algorithms, sensory feedback systems, and mechanical designs that provide sufficient stability and adaptability [2]. In recent years, there has been a growing interest in robot development, specifically focusing on hybrid mechanisms and locomotion. These developments involve combining two or more different

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configurations and mechanisms within a single robot unit that require transformation modes. One such innovative concept is the Bipedal Wheel-Legged (BWL) robot, which effectively merges the advantages of both wheels and legs to offer versatile locomotion for a wide range of applications [3], [4].

BWL robots, which combine the agility of legged robots with the mobility of wheeled counterparts, are reshaping the landscape of mobile assistive systems. These robots feature three primary locomotion modes: bipedal walking, bipedal skiing, and rolling, enabling both stable walking and rapid rolling [4]-[7]. Their ability to seamlessly switch between these modes is crucial for adapting to diverse environments [6]. However, achieving such versatility is a complex endeavor due to inherent dynamic interactions and uncertainties, necessitating refined control strategies, precise modeling, and adaptable systems [8], [9]. A central concern revolves around stability and balance. In contrast to traditional wheeled robots, these robotic systems have a relatively high center of gravity, making them susceptible to balance disruptions, especially when navigating uneven terrains. These tendencies can result in undesired outcomes like tilting or toppling [7], [10], [11]. Transition phases, where the robot transitions from wheeled to legged motion and vice versa, are exceptionally delicate junctures. Therefore, ensuring flawless coordination between the robot's limbs and wheel mechanisms during these transitions is imperative [12]. Although they exhibit commendable performance on flat landscapes, their design sometimes hinders unhindered movement on more challenging terrains [7]. Tailoring control strategies to enable seamless mode transitions based on terrain intricacies is crucial [13].

A significant portion of the research has been dedicated to dynamic motion control. The fusion of wheel and leg locomotion inherently presents a complex control challenge. Their distinct operational modes underscore the critical need for achieving a delicate balance [12]. Given the volatile nature of the terrains these robots navigate, which often include unexpected obstacles, there is a strong imperative to develop control algorithms that are both adaptive and predictive [14]-[16]. The intricacies involved in design, particularly when striving to replicate the subtleties of human movement, add further layers of complexity to robotic architecture. Such efforts demand a seamless integration of sophisticated mechanical designs and actuation systems [10], [17]. An equally pressing challenge lies in engineering these robots to be lightweight and robust, ensuring they can withstand the multifaceted demands posed by various terrains [18], [19]. In the realm of energy optimization, while bipedal movement is theoretically efficient, translating this theoretical efficiency into tangible outcomes is an intricate task. Achieving the perfect balance of energy demands between the wheels and leg actuators is especially critical when dealing with complex leg configurations [14], [20]. Delving into the realm of control, the robots' extensive degrees of freedom and intricate balance dynamics render their control more intricate compared to conventional robotic systems [14], [15]. These challenges necessitate innovative solutions, with advanced control methodologies such as model predictive and optimization-based frameworks becoming indispensable. Particularly for robots equipped with expansive leg mechanisms, the coordination of wheel and leg motions requires a higher level of algorithmic and sensorial sophistication [21] .

In summary, BWL robots represent a groundbreaking evolution in robotics, offering unmatched adaptability for terrain navigation and various tasks [22]. However, they face significant challenges that ongoing research focuses on: perfecting their design, refining control mechanisms, and optimizing energy dynamics [23]. This review provides a comprehensive overview of these challenges. It specifically examines their adaptability to diverse terrains, explores how sensory feedback integrates with control mechanisms, and looks at efforts to replicate human-like movements. Additionally, the review sheds light on the robots' transition stages and potential future advancements. It underscores the critical importance of interdisciplinary collaboration for further progress in this field.

2. Evolution and Terrain Adaptability in Bipedal Wheel-Legged Robotics

The emergence of wheel-legged robots represents a significant leap forward in the domains of robotics and control engineering. The more extreme mechanism such as BWL was introduced in the last 10-15 years to provide more agility to this kind of mobile robot. Equipped with dynamically stable mechanism, BWL robot open to a new challenging in its control engineering area especially to sustain the attitude stability in parallel with agility control. This technological breakthrough can be traced back to the 1980s, when Honda initiated research into bipedal locomotion [24]. Subsequently, this field has witnessed substantial advancements, most notably marked by the introduction of the inaugural Zero Moment Point (ZMP) based robot in 1985, which achieved dynamic bipedal walking [25]. These robots, incorporating both legged and wheeled attributes, have gained commendation for their adaptability and efficiency across various terrains, be they uneven or smooth [5], [22], [26]. Furthermore, there has been a growing fascination with these robots due to their distinctive fusion of wheeled maneuverability and legged dexterity [27]. Undoubtedly, wheel-legged robots have revolutionized the realm of mobile robotics by seamlessly amalgamating the merits of legged and wheeled systems. They find extensive industrial applications, including, but not limited to, urban logistics, disaster relief, and industrial inspections [28], [29].

Nevertheless, the significance of wheel-legged robots extends far beyond mere adaptability. Their design excels in maneuvering through uneven terrains and confined spaces, rendering them invaluable for a plethora of applications. The harmonious integration of wheels and legs not only ensures heightened mobility across various surfaces [21], but it also bolsters stability, thereby reducing the likelihood of toppling mishaps [30]. Moreover, they exhibit remarkable versatility, capable of adjusting their movement strategy in response to varying terrain conditions, thereby enhancing agility [30], [31]. Expanding their utility even further, wheel-legged robots find relevance across diverse sectors. For example, their exceptional ability to navigate challenging terrains positions them ideally for search and rescue missions during emergencies [32]. Their presence is pushing the boundaries of exploration into previously inaccessible realms, such as caves, confined tunnels and pipeline as well as shallow underwater [31]. Moreover, they are deployed by military forces to conduct reconnaissance in rugged landscapes such as reported in [33]. On the other hand, in manufacturing industries, wheel-legged robot agility has been leveraged to efficiently manage the materials within intricate industrial settings such as reported in [34]. At the forefront of this groundbreaking field stands Swiss-Mile, a creation of ETH Zurich's Robotic Systems Lab. As can be seen in Fig. 1(a), Swiss-Mile's agility in seamlessly transitioning between quad and bipedal stances highlights the significant progress made in the development of robotics tailored for environments centered around human interaction [35], [36].

Another remarkable entity worth mentioning is Handle by Boston Dynamics as shown in Fig. 1 (b). Its design features passive wheels and an innovative balancing tail, emphasizing adaptability, especially during material handling tasks [37], [38]. This concept later evolved into "Stretch" in 2019, optimized for warehouse operations, as seen in Fig. 1(c) [37], [39] . Notable examples of BWL robots include SR600 and BHR-W [40]. Despite the field's progress, several challenges remain in designing and controlling these robots, including issues like poor balance, limited mobility, dynamic motion control, transformation problems, and planning and control strategies [24]. The genius behind these robots lies in their integration of kinematics, dynamics, and a deep understanding of terrain interactions [41]-[43]. They prioritize energy conservation and stability while using advanced control algorithms for navigating complex terrains [44]-[53]. Machine learning further enhances their adaptability [54].

The collaborative project "Little HERMES" between the University of Illinois and MIT underscores these robotic systems' transformative potential. By mimicking human leg dynamics, it offers a versatile range of movement for various experiments [55]-[57] as shown in Fig. 2(a). Design elements like the Stewart platform and large wheels enhance obstacle navigation while maintaining stability. Robots come in diverse designs, such as asymmetric, symmetric, transformable, and integrated configurations, tailored for specific terrains and movement needs [4], [43], [58]-[66].

Asymmetric designs excel on tough terrains, symmetric ones ensure stability [65], [66]. Transformable robots switch between legged and wheeled modes, and integrated systems combine wheel and leg mechanisms for agile movement [63]. Drawing from biomimicry, legged robot mechanisms offer a versatile range of movement, using controlled actuators, sensors for precise foot placement, and algorithms for navigation [38], [67]. Some integrate wheels for efficiency and adaptability, especially in environments with obstacles [63]. In essence, legged robots navigate challenging terrains more adeptly than purely wheeled counterparts.

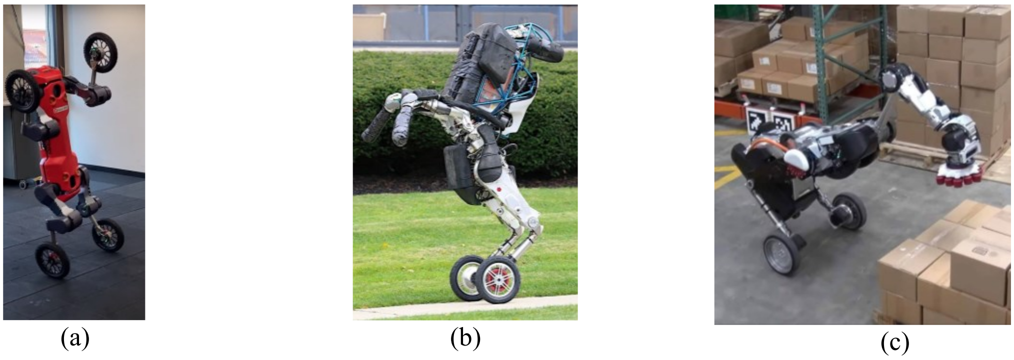

(a) (b) (c)

Fig. 1. Example of recent wheel-legged robot prototype/products; (a) Swiss-Mile in bipedal mode, (b) Handle and (c) Stretch from Boston Dynamics

Another notable player in this field is ETH Zurich's "Ascento." Despite its compact weight of 10.4 kg, this robot features jump-enabled wheeled legs that smoothly traverse obstacles and flat terrains [68]. As shown in Fig. 2(b), ongoing research is concentrated on dissecting and enhancing the robot's jumping and balancing dynamics as reported in [7], [40]. Recent efforts focus on merging bipedal walking and wheel movements, expanding their utility and redefining robotic mobility standards [22], [43], [63]-[66], [69] . Leading this effort are studies by V. S. Raghavan *et al.* and M. Bjelonic *et al.* They have brought a human touch to robotic design, preparing them for diverse real-world challenges [51], [59]. Expanding upon these foundations, there are additional pioneering research efforts that have diligently examined the adaptability of these robots on various terrains [3], [4], [47]. These endeavors are rooted in fundamental principles and mechanical innovations, as detailed in other pivotal studies [43], [64], [70]-[72]. Key contributors such as J. Li *et al.* and W. Wang *et al.* have emphasized the significant role played by components like elastic actuators, compliant joints, and integrated sensors [64], [73]. These elements enhance the robot's dynamic performance. Additionally, research in [66] had explored resilient materials and state-of-the-art sensors, demonstrating their value in these robotic advancements. In summary, BWL robots are spearheading a revolution in mobile robotics. They demonstrate remarkable adaptability, effortlessly transitioning between various terrains and modes in response to environmental demands. Their designs, enhanced by advanced control strategies, embody cutting-edge progress in the field of robotics. We find ourselves on the brink of a transformative era in robotics, where these innovations continually push industry standards to unprecedented heights. The fusion of design excellence and adaptability heralds an exciting trajectory for the future of robotic innovation.

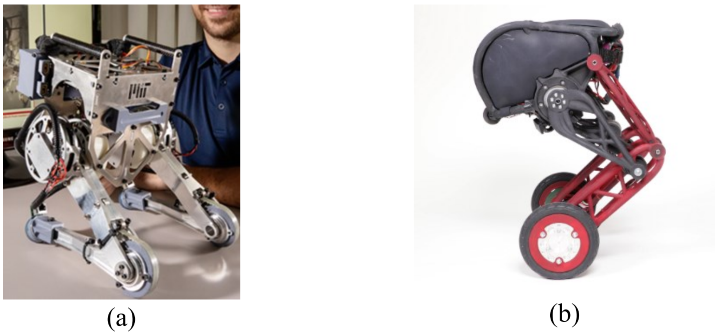

(a) (b)

Fig. 2. Example of BWL robot prototype/products; (a) Little Hermes (b) Ascento Robot

3. Stability, and Locomotion in Bipedal Wheel-Legged Robots

In recent years, academic interest in BWL robotics has grown significantly due to its innovative combination of wheeled motion with bipedal balance [40], [74]-[76]. This fusion brings to the forefront fundamental aspects of hybrid movement: gait planning, balance control, trajectory formulation, and real-time feedback, all crucial for enhancing robotic functionality [12], [77], [78]. As the field advances, the need for adaptive behavior in bipedal robots becomes evident for optimal performance. Recent innovations offer cost-effective adaptive capabilities, although challenges such as control instabilities related to trajectory [79], [80], limitations of adaptive control algorithms in real-time scenarios [122], tracking anomalies, and computational burdens with Model Predictive Control (MPC) persist [81], [82]. Addressing these challenges has the potential to revolutionize energy efficiency in bipedal movements [5], [12], [83].

Modern robotics increasingly relies on sophisticated control systems as seen in bipedal wheel-leg robots designed for agility [84]. Advanced methods like decoupling control, Electrical-Jet assistance, and robotic jumping have improved dynamic balance capabilities [7], [32], [85]. Compliant walking controllers enhance navigation in challenging terrains [86], bridging the gap between robots and authentic bipedal locomotion for enhanced stability and efficiency [87]. Features such as the six degree of freedom (DOF) parallel link mechanism improve leg inertia and position tracking at higher frequencies [42], [87]. Current research focuses on refining robotic locomotion across irregular terrains [43]. While methods like MPC excel in precise vehicular trajectory control [88], challenges arise in scenarios with abrupt changes. Strategies like heuristic landing planners, dynamic foot positioning, and preference-driven controller optimization have enhanced robot efficiency [42], [89]. Additionally, advanced control frameworks like force-and-moment-based MPC and model hierarchy predictive control (MHPC), along with innovations like sensor-based active elastic hip joints and spring-based passive elastic knee/ankle joints, promise to optimize robotic stability and movements [44], [64].

In contemporary research, dynamic and optimal control algorithms are key [90], [91], ensuring stability during various conditions such as mode transitions, balance adjustments, and shifts in the robot's center of mass [12], [85]. These factors are central to a robot's adaptability, resilience, and energy conservation [43], [92], [93]. Recent designs like the manipulator-armed attached on wheel-legged robot [94], [95] and the agile hydraulic robot [96], [97], exemplify these state-of-the-art control and stability features. Breakthroughs emphasize hardware capacities, algorithmic optimizations, and perception mechanisms [98]. Fig. 3 visually represents a bipedal wheel-legged robot with an arm manipulator [97] and a robot equipped with a jumping mechanism [95]. Despite recent advancements, certain obstacles remain. These include high computational demands, limitations in intricate environments, dependence on training data quality, and specialized designs that compromise versatility [88], [99], [100]. To address these challenges, proposed solutions involve integrating multiple control strategies like MPC, optimal trajectory planning, and reinforcement learning [101]-[104]. Hierarchical control approaches have also emerged to improve robot arm collaboration, enabling efficient multitasking while preventing collisions [105]. A comprehensive exploration of diverse methodologies, including hierarchical control structures, genetic algorithms, virtual suspension model control, and multi-task control strategies, has deepened our understanding of multilegged robotic dynamics [80], [106]-[111].

To provide a holistic view, Table 1 to Table 5 offer a comparative analysis of control techniques in bipedal and wheel-legged robotic systems. They highlight distinctive features, benefits, and limitations. For instance, Table 1 delves into gait optimization strategies, while Table 2 focuses on balance enhancement mechanisms, and so on. This thorough analysis provides profound insights into the dynamic controls of these robots, outlining challenges and potential pathways for progress. In the future, groundbreaking methods such as Behavior-Based Reinforcement Learning and Optimization-Inspired Design are on the verge of transforming robotic locomotion [120]-[122]. The literature underscores the essential role that control algorithms play in this transformative process. The outlook for bipedal wheel-legged robots is promising, with the robotics field indicating exceptional adaptability and efficiency, heralding the start of an exciting era of research and innovation.

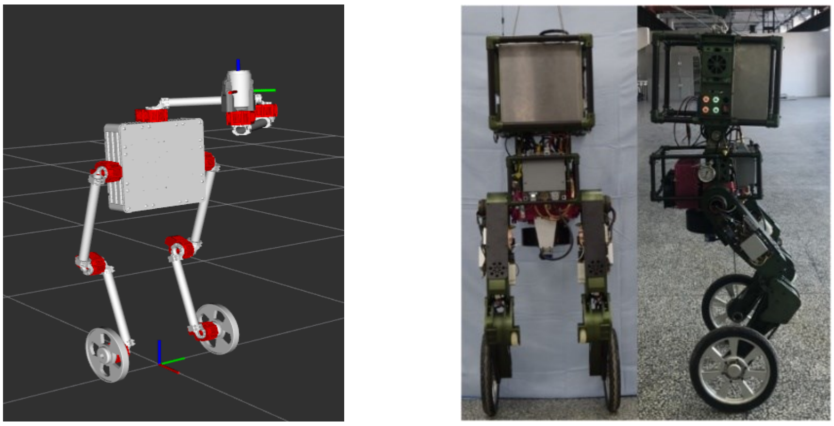

(a) (b)

Fig. 3. Example of BWL prototypes; (a) BWL with manipulator arm, (b) Autonomous BWL

Table 1. List of Gait Planning Control Technique in Wheel-Legged Robot Design

Control Technique	Description	Key Features	Advantages	Limitations
Heuristic Gait Template Planning [112].	A method that plans trajectory according to various robot dynamics.	Trajectory determined by factors like speed, cycle, and support height.	Straightforward to implement, offering a simpler system.	It struggles with adaptability when the robot faces multifaceted terrains.
Variable Spring-Loaded Inverted Pendulum Model with Finite-sized Foot (VSLIP-FF) [113].	An enhancement of the SLIP model incorporating a finite-sized foot and a 1-DoF ankle.	Extends the basic SLIP model for enhanced mobility.	Paves the way for navigation in intricate environments.	It introduces complexities beyond the conventional SLIP model.
Velocity-Based Gait Planning [114], [115].	A technique that relies on a linear spring-damper model for foot-ground interaction.	Optimizes foot-ground contact dynamics for gait planning.	Shows efficacy on uneven and flexible grounds.	Its prowess diminishes in highly dynamic scenarios.
Real-Time Motion Planning Using Proximity Information [116].	Leverages proximity sensors to optimize foot placement.	Proximity sensors attached to each foot facilitate real-time trajectory adjustments.	Allows for instant trajectory alterations based on sensor feedback.	Its effectiveness might wane on certain complex terrains.
Energy-Efficient Gait Planning [117].	Focuses on power conservation using a sophisticated pendulum model.	Utilizes a 3D motion and AZR model based on a five-mass inverted pendulum concept.	Pioneers' energy-efficient bipedal movement.	The energy index function and motion space can be intricate to decipher and implement.

Table 2. List of Balance Control Technique in Wheel-Legged Robot Design

Control Technique	Description	Key Features	Advantages	Limitations
Active Arm Control [116].	A technique leveraging the robot's upper limbs for balance enhancement.	Employs upper limbs for balance recovery.	Provides notable improvements in stability and robustness.	Introduces the need for additional mechanical components, potentially complicating design.
Behavior Cloning [118].	An approach that mimics human balance behaviors through deep learning.	Utilizes DNNs trained on human-operated balancing data.	Achieves superior resistance to balance loss due to human-	The efficacy heavily relies on extensive and varied training data,

Control Technique	Description	Key Features	Advantages	Limitations
			like behavior replication.	which can be challenging to obtain.
Central Pattern Generator (CPG) with Defined Pulse Signals [78].	A method designed to produce balance-centric behaviors resisting compliance.	Generates behavior resistant to compliance for biped robot stability.	Ensures effective balance, especially on uneven terrains.	Might necessitate specific fine-tuning adjustments when transitioning between different environments.
Behavior-Based Reinforcement Learning Approach [119].	A modular approach dividing bipedal walking into distinct tasks and behaviors.	Categorizes bipedal walking into specific tasks and control behaviors.	Offers enhanced resistance against disturbances due to its segmented nature.	Introduces computational challenges inherent to reinforcement learning.
Ultra-Lightweight, Knee-less Leg Design [74].	A novel design strategy focusing on reducing leg weight without compromising its core functions.	Decreases leg weight while upholding its full functionality.	Curtails vertical motion in robot's Center of Mass during walking, enhancing balance.	Poses a challenge as it demands an extensive redesign of pre-existing leg structures.

Table 3. List of Learning Adaptation Control Technique and Optimization Approaches in Wheel-Legged Robot Design

Control Technique	Description	Key Features	Advantages	Limitations
Behavior-Based Reinforcement Learning Approach [123].	A method that leverages reinforcement learning for bipedal robot locomotion control.	Proposes a behavior-based locomotion controller using RL.	It offers adaptability in locomotion strategies via RL, potentially enhancing robot adaptability.	The technique can be computationally demanding and necessitates vast amounts of training data.
Standing Balance Control Based on Behavior Cloning [100].	An innovative method that employs behavior cloning for standing balance in bipedal robots.	A balance controller rooted in behavior cloning.	Achieves superior balance control by harnessing the power of machine learning.	Its efficiency is heavily tied to the quality and generalizability of its training
Integration of RL with MPC [124]-[126].	An approach that combines Reinforcement Learning with Model Predictive Control for bipedal robot efficiency.	Optimizes prediction horizons and multi-energy systems.	Marks significant advancements in bipedal robot technology, offering a blend of predictive and adaptive capabilities.	The technique's success is contingent on the quality and volume of training data it receives.
Continuous Markov Decision Processes [99].	An optimization-based approach challenging conventional Model Predictive Control assumptions.	Uses optimization-based approach.	It provides a fresh perspective that can lead to better results than traditional MPC.	One of its key limitations is the high computational resources it demands.
RL for MPC Parameter Tuning [127].	Approach to enhance Model Predictive Control by fine-tuning its parameters via Reinforcement Learning.	Fine-tunes MPC parameters.	Potentially superior performance compared to traditional parameter optimization techniques.	Issues may arise related to convergence and the determination of an optimal policy.

Table 4. List of Trajectory Generation Control Technique in Wheel-Legged Robot Design

Control Technique	Description	Key Features	Advantages	Limitations
ZMP-Based Trajectory Generation Using Quadratic	Leverages Zero Moment Point (ZMP) methods combined with quadratic programming algorithms	Uses ZMP methods with a quadratic programming algorithm.	Promises real-time stability for the robot, a crucial factor in various operational settings.	The technique is computationally demanding, especially during real-time optimization, which

Control Technique	Description	Key Features	Advantages	Limitations
Programming [100].	to generate real-time stable trajectories.			may limit its applications.
Body Trajectory Generation Using Quadratic Programming [74].	Adapts existing methods from quadruped robots for use in bipedal systems.	Real-time stability and minimized acceleration.	It offers real-time stability and optimized acceleration, making it a potentially powerful option for bipedal robot control.	The stability and performance might deteriorate when adopting methods originally designed for quadruped robots.
Optimization-Inspired Design [128].	Deploys trajectory optimization techniques for enhancing the agility and acceleration of bipedal robots.	Utilizes trajectory optimization techniques.	Notably enhances agility and rapid acceleration, which could be pivotal in certain operational scenarios.	The method requires meticulous design and fine-tuning of the optimization algorithms, which could be resource-intensive.
Compliant Control Approach [129].	Implements a compliant control approach that combines Divergent Component of Motion (DCM) error and Center of Pressure (CoP) trajectory modification.	Uses DCM error and CoP trajectory modification.	Improves stability on soft and uncertain terrain, potentially widening the operational scope of bipedal robots.	The technique may necessitate parameter tuning for different terrains, adding to the complexity of its implementation.

Table 5. List of Feedback Control Technique in Wheel-Legged Robot Design

Control Technique	Description	Key Features	Advantages	Limitations
External Motion Capture System [99].	A control methodology using an external system to capture motion, providing feedback for system state.	Uses an external motion capture system for accurate state feedback.	Boasts accurate and consistent state feedback, a critical factor in optimizing robot motion.	Relies heavily on the presence and functionality of external motion capture infrastructure, limiting its standalone capabilities.
ZMP Compensation [88].	A stabilization technique using Zero Moment Point (ZMP) compensation.	Implements ZMP compensation techniques for better stabilization.	Provides robustness against disturbances and high responsiveness, ensuring stable robot operations even in challenging scenarios.	Needs careful tuning of feedback parameters, making it a more hands-on approach.
Swing Leg Control [130].	Utilizes the swing leg for real-time feedback and control.	Uses swing leg control for real-time feedback mechanisms.	Reduces the Center of Mass (CoM) tracking error and improves steady-state convergence, leading to smoother robot movement.	Relies on the availability and accuracy of system state feedback, and errors can disrupt robot balance.
Sensor Fusion [131].	An approach combining data from multiple sensors to enhance robot perception.	Integrates information from various sensors for a comprehensive view.	Achieves accurate and resilient localization and situational awareness, giving the robot a robust understanding of its environment.	The process can be intricate due to the challenges in data fusion and processing, potentially increasing the computational load.
Model Predictive Control (MPC) [132].	A control strategy employing model predictive controls for real-time operations.	Implements a computationally efficient MPC for instantaneous control.	Enables real-time control of fast-dynamic humanoid robots, allowing for quick adjustments and responses.	Relying on approximations in the robot model might affect the control's accuracy, especially over longer operational durations.

4. Bipedal Wheel-Legged Robot Performance: Advancements and Challenges

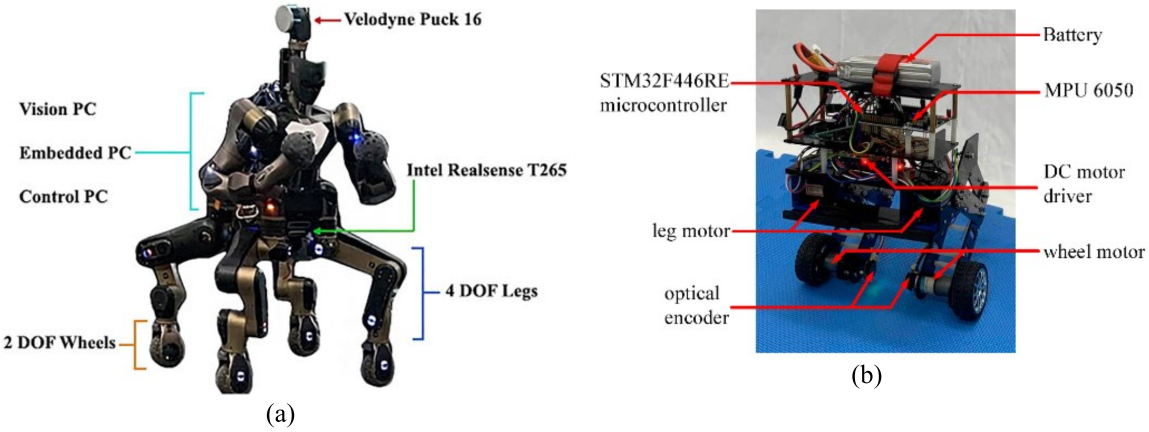
BWL robots, currently leading the way in robotics research, have attracted considerable attention due to their intricate designs and the challenges they pose in terms of balance and locomotion control [23]. To address these challenges, researchers have turned to advanced control systems, machine learning, computer vision, and sensor fusion [85]. These innovations are pivotal in pushing the boundaries of bipedal robot capabilities. Taking inspiration from human locomotion, bipedal robots have witnessed significant advancements in their design, aiming to mimic human stability and efficiency [43]. BRUCE serves as an exemplary illustration of this progress, serving both research and educational purposes. Featuring distinctive BEAR proprioceptive actuators, BRUCE offers exceptional dynamic performance capabilities. Weighing 4.8kg and standing at a height of 70cm, BRUCE boasts an impressive 16 degrees of freedom. With a 3000mAh battery, it guarantees approximately 20 minutes of uninterrupted operation, and its liquid-cooled knee actuators further enhance its movement efficiency [133], [134] . Key technologies, such as cable-driven differential pulleys and Model Hierarchy Predictive Control (MHPC), ensure that robots operate with real-time precision, even in unpredictable environments [43], [70]. These innovative control mechanisms underscore the evolving benchmark for upcoming robotics breakthroughs [70]. The continual advancements in bipedal wheel-leg robot research are not just enhancing robotics but also unlocking transformative potentials across multiple industries [7], [11], [15], [32], [85]. As these robots find more real-world applications, their relevance and impact on the future trajectory of robotics become even more profound [4], [5], [13]. Their evaluation often pivots on efficiency and maneuverability [85], [135], [136]. To address the challenges of navigating diverse terrains, there's a rising interest in hybrid maneuverability. This approach synergizes wheeled and legged locomotion, offering enhanced versatility [78], [99], [137], [138].

The development of efficient BWL robots involves the use of lightweight materials, sophisticated control algorithms, and innovative actuation systems, all converging to minimize energy consumption [139]. Researchers are proposing unique locomotion mechanisms and adaptable wheel legs for effective navigation across diverse environments [26], [30], [38]. The intricacies of mechanical design, especially in components like hip, knee, and ankle joints, are paramount for these robots' performance [140]. Jones *et al.* emphasized that aligning the robot's physical design with its intended functionalities is pivotal for optimizing movement [12]. A meticulous mechanical design, complemented by durable yet lightweight materials and sensors, ensures the robot's adaptability and efficiency, even in challenging terrains [40].

In brief, BWL robots are at the forefront of a robotics revolution, driven by innovative mechanical designs and advanced control systems. Their expanding practical applications, versatile locomotion capabilities, and energy-efficient features signify a pivotal transformation within the industry. The fusion of both wheeled and legged movement provides solutions for a wide array of terrains, while the harmonious interplay between design and functionality, reinforced by robust materials, enhances their adaptability for industrial purposes. These robots represent a significant leap forward in robotics, poised to exert a profound impact across various sectors. Their evolution, molded by cutting-edge technology and efficiency-centric designs, lays the foundation for remarkable advancements in the field.

5. Controller Unit, Sensory and Perception Systems in Bipedal Wheel-Leg Robot Design

In the field of robotics and control engineering, there is a growing focus on designing BWL robots, with a particular emphasis on integrating sensory systems [4], [40]. Achieving a balance between sensory and perception systems is vital for enhancing robot performance, as widely practiced in this research community. Inspired by legged robot designs like Boston Dynamics' Atlas and IIT's HyQ2 [141], successful robot locomotion relies on precise leg actuator control and accurate sensor interpretation [142]. Research on ground reaction forces and predictive angular momentum informs locomotion dynamics, paving the way for future studies in bipedal wheel-legged robots [12], [63], [143]. It's essential to establish perception-based and sensory-based control designs before integrating them into most legged robot designs, as reported in [144], [145], to ensure fast responses in leg motion and interaction. This principle applies to wheel-legged robots as well. Recent developments highlight sensor integration's significance for stability and adaptability across different environments [105]. Notably, the incorporation of sensors like Light Detection and Ranging (LIDAR) is essential for tasks such as three dimensional (3D) mapping, obstacle detection, and motion planning [146]. Adverse weather conditions can affect system efficacy, emphasizing the need for complementary sensors to ensure consistent robot performance [84], [123], [147]. Fig. 4 visually example of wheel-legged robot with control system features



(a)

(b)

Fig. 4. Example of wheel-legged robot with control system features; (a) CENTAURO hybrid legged/wheeled [18], (b) BWL named WBR [21]

For example, robots like Boston Dynamics' Atlas and IIT's HyQ2, with 28 and 12 hydraulically actuated joints respectively, feature the Carnegie Robotics Multisense SL sensor head, including a rotating LIDAR scanner and stereo camera, enabling them to navigate challenging terrains and hinting at a more capable robot future [141]. Vision systems, combined with LIDAR and Inertial Measurement Units (IMUs), improve object recognition, landmark identification, navigation, and overall perception [124], [147]. Combining kinematic data with information from inertial, vision, and LIDAR systems significantly improves localization precision in bipedal robots [126].

IMUs, which measure force, orientation, and velocity, play a crucial role in maintaining balance, coordinating gait, and ensuring stability [124]. When combined with cost-effective joint encoders, IMUs improve the assessment of joint angles, enhancing our understanding of spatial orientation [123], [138], [147]. Innovations such as integrating visual-LIDAR-based 3D tracking with neural networks are pushing the boundaries of visual classification [125]. Measuring force or torque enables robots to interact effectively with their environment, facilitating tasks like object manipulation and balance maintenance [156]. Sensors like ultrasonic and infrared proximity sensors, as well as range sensors, are instrumental in environmental mapping and collision prevention [78], [157]. Terrain sensors provide valuable data, enabling adaptive movement strategies to ensure stability and efficiency across various terrains [74], [149], [158]. Table 6 compiles these advancements, highlighting the diverse sensors used for terrain recognition and control in bipedal robots, including bio-inspired feet and neural network terrain classification [149], [151], [154], [155].

All of these achievements can be realized through a suitable selection of processing units, such as embedded systems, computer units, microcontrollers, or microprocessor units. Like other automation systems, choosing the right processing unit is critical in robot development, especially in the case of BWL robots. This choice is essential to ensure the system's objectives and efficiency are met. Notably, embedded system boards like Arduino and the STM32 microcontroller series are prominent players in this field, efficiently handling complex sensor inputs, including those initiated by human operators, thus enabling seamless interaction with actuators and motors [159].

Additionally, for tasks involving high-definition and complex algorithm computations, a single-board computer (SBC) or microcomputer, such as Raspberry Pi, Rock Pi, NVIDIA Jetson, and others, may be preferred. In the context of legged robot systems like BWL, a suitable SBC enables effective coordination and control of both legs and wheels, seamlessly integrating with other electronic components [12], [21]. Moreover, effective multitasking operations can be achieved by selecting an appropriate SBC or microcontroller unit (MCU) with sufficient capacity. For instance, if a robot is designed for fire mitigation, requiring inspection and action, it would need at least a camera, flame sensors, and an established communication protocol to operate as intended [160], [161]. Furthermore, the processing unit must be capable of controlling leg joints simultaneously or performing parallel processing actions, as demonstrated in [162], [163]. Alternatively, some designs may only require a single MCU with high speed and capacity, such as the STM32 with ARM Cortex processing unit. This MCU, when paired with a development board, offers versatility in handling both MCU and SBC capabilities. For example, in [12], an ARM-Cortex STM32F4 was configured and programmed to efficiently manage both IMUs and communication between leg joints using an impressive 200Hz Bluetooth protocol. Similar performance can be observed in the BWL robot system reported in [164], where the STM32H7 series was deployed to handle all driven devices and communication systems simultaneously. The deployment of the proposed controller was successfully verified to provide stable locomotion and wheeling capabilities across challenging terrains.

Table 6. List of Sensor Systems that deployed in various Bipedal Robots

Sensor System	Author	Main Contributions	Sensor Types Used
Terrain Sensors	Kim *et al.* [74], Kuo *et al.* [99], Almeida *et al.* [148].	Bio-inspired robot foot design; Online training and AR for terrain classification; Comparison of ML techniques for terrain identification	Acoustic, Capacitive, Tactile, Temperature, Acceleration, Force, Position, Current, Inertial sensors
	de Souza *et al.* [149], Kajita *et al.* [150], Zhang *et al.* [151].	Terrain identification using neural networks; Motion planning using proximity sensors; Viscoelastic model for contact force/torque control	Inertial, Torque, Proximity, Force/torque sensors
Joint Encoders	Kim *et al.* [44], de Souza *et al.* [116], Kuo *et al.* [152], Zhang *et al.* [153].	Foot-mounted ZMP sensor design; ZMP computation using wireless foot sensor modules; Dead reckoning for high-rate feedback control; Bio-inspired robot foot design with sensor suite	Joint Encoders, Force Sensing Resistors (FSR), Inertial Sensors
	Zhang *et al.* [154], Hydra *et al.* [155].	Sensor data fusion for spatial motion estimation; Use of EHA for force-sensitive robots	Joint Encoders, Inertial measurement unit, Inclinometer, Pressure sensors, IMU

In brief, the incorporation of a variety of sensors, encompassing LIDAR, vision systems, and IMUs, substantially bolsters the adaptability and performance of automation systems, particularly in the case of BWL robots. Furthermore, the synergy between sensory data, machine learning, and neural networks is transforming the landscape of motion planning, terrain recognition, and locomotion control, offering a promising outlook for the deployment of these robots across diverse industries. Primarily, the meticulous selection of SBC or MCU, coupled with the efficient integration of both units, stands as a pivotal factor in achieving stable functionality and seamless operation in BWL robots. This approach not only optimizes the capabilities of configured sensors and perception systems but also ensures the robot's overall reliability.

6. Contemporary Cutting-edge and Technology of Bipedal Wheel-Leg Robot

The shift in robotic research from traditional methodologies towards the incorporation of advanced sensory systems is well-demonstrated by the significant progress in bipedal wheel-legged robots, such as Handle [4], [5], [13]. This development is not merely incremental; it is indeed a transformative leap, heralding an era marked by exceptional adaptability and performance enhancement. The increasing versatility of these robotic systems has expanded their potential applications, thus enhancing the relevance of both bipedal and wheel-legged bipedal robots across various sectors [11], [15], [69], [165].

Drawing from the complexity of human biology, innovative design principles and mechanical frameworks have not only advanced the robotics sector but also provide insight into the evolutionary journey, present status, and potential future of bipedal wheel-legged robots. This spans a multitude of elements from mechanical design, artificial intelligence integration, to the challenges they introduce [23]. Significant contributions by Y. Ni *et al.* (2022) and I. Fadelli (2022) have been instrumental in revealing the potential of these robots, highlighting the benefits of merging legs with wheels for enhanced mobility and adaptability [166].

The evolution in design has significantly improved the maneuverability of bipedal robots, facilitating their navigation through complex terrains and enabling easier stair-climbing capabilities. Contemporary research, intersecting domains such as material science, compliant mechanisms, actuation techniques, sensor technologies, energy management, and control systems, has instigated a pivotal transformation in bipedal wheel-legged robotics [74], [167], [168]. These technological strides have enhanced the performance longevity of robots, paving the way for a new epoch in robotic prowess.

Diverting from traditional design ideologies, materials such as advanced polymers, carbon fiber composites, and titanium alloys are becoming increasingly prevalent due to their optimal balance of lightweight and durability [138], [169]. For instance, robots like SLIDER exemplify the benefits of these advancements, promoting energy-efficient systems [74]. The SLIDER's unique design approach, shifting from traditional knee-driven movement to leg sliding from the hips, provides numerous benefits like decreased weight, cost reduction, and a center of mass positioned nearer to the pelvis [170]. Moreover, the integration of compliant elements, including flexible joints, bolsters resilience and amplifies energy efficiency [171]-[173].

A prime example of sophisticated robotic mobility is epitomized by Ascento, displaying agility on uniform terrains and dynamically surmounting barriers using jumping strategies. With a comprehensive sensor array consisting of cameras, LIDAR, radar, and thermal imaging, Ascento possesses heightened situational cognizance, adeptly identifying anomalies. These robots maintain consistent communication with a central command, facilitating real-time incident updates. Notably, Ascento employs Artificial Intelligence (AI) and Machine Learning (ML) to refine its detection capacities continuously [174], [175].

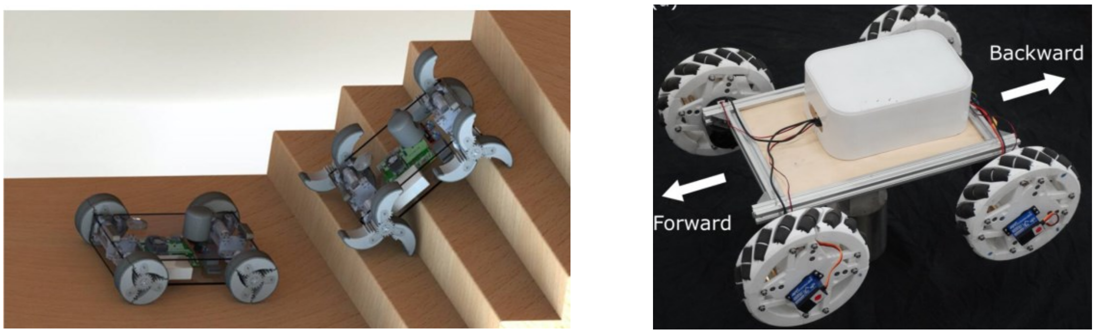
The evolution of actuation systems stands as another pivotal facet, where cutting-edge technologies like brushless motors and piezoelectric actuators assume a leading role [88]. These technological advancements contribute to the development of more energy-efficient and agile robots, as demonstrated by the SLIDER platform [88], [172]. Progress in sensor technologies ensures that the integration of compact sensors enhances the robot's environmental perception and operational control [169], [176] Simultaneously, innovations in power management and the utilization of high-endurance batteries amplify the robot's operational duration, signifying a fertile ground for upcoming research explorations [74], [88], [177].

From a software perspective, cutting-edge control algorithms play a pivotal role in executing intricate tasks such as gait planning, stability control, and motion coordination [169]. These systems are instrumental in achieving agile and efficient locomotion, thereby pushing the boundaries of what is currently achievable. To wrap up, the interdisciplinary advancements in material science, actuation systems, sensor technologies, and control algorithms synergistically contribute to the rapid advancement of bipedal wheel-legged robots. The research landscape in this domain is flourishing, offering the promise of even greater performance, durability, and efficiency in the future. An understanding of these diverse facets is imperative for comprehending the forthcoming trajectory in this burgeoning field.

7. Future Directions of Control s and Design in Bipedal Wheel-Legged Robotics

Bipedal wheel-legged robotics is a rapidly evolving field, marked by substantial design and control strategy advancements. Such innovations offer transformative opportunities for mobile assistive systems, especially in challenging environments [40]. As this domain progresses, it promises a future where robots exemplify agility and adaptability [9], [67], [178]-[180]. Notably, these advancements' primary focus is enhancing control strategies, allowing robots to manage intricate transitions and navigate unforeseen environments seamlessly [51], [74], [75], [181], [182]. Central to this progression is integrating predictive control, trajectory planning, and reinforcement learning, all contributing synergistically to optimize robotic performance [90], [91], [103], [104]. Furthermore, by factoring in the intricacies of diverse terrains and varied operational conditions, the practicality and versatility of these robots in real-world settings become increasingly evident [78], [80], [92], [93], [99], [136], [138], [183]-[185].

Recent studies in robotics and control engineering emphasize the significance of wheel-biped transformable robots that employ hybrid control systems. Such systems adeptly integrate trajectory planning, feedback control, and machine learning techniques, forming a robust blend of advanced control mechanisms [41], [186]. Among these, reinforcement learning is crucial, aiding in seamless transitions between wheeled and legged movements, ensuring efficient balance, and enabling instantaneous use of sensor data [43], [186], [187]. However, a transformative advancement in this domain is the integration of wheel-leg mechanisms into bipedal robots, which considerably bolsters their stability, efficiency, and adaptability [12], [94], [105]. For instance, the OmniWheg robot, which possesses self-adjustment capabilities, is a testament to the notable progress in environmental navigation technology, as illustrated in Fig. 5(b) [140].



(a) (b)

Fig. 5. (a) Concept illustration of the adaptable Wheel-and-Leg Transformable Robot [205], (b) OmniWheg is a self-adapting robot for environmental navigation [12]

Groundbreaking innovations, such as a three-mode locomotion system and a six-degrees-of-freedom (6-DOF) bipedal robot, further underscore the advancements in this field [188]-[197]. The fusion of these advanced robotic structures with sophisticated control techniques enhances their proficiency in responding to emergencies and exploring unfamiliar terrains [122], [192], [193], [198]. Additionally, the adoption of simplified control frameworks, kinematic control models, and transformation methods results in superior velocity tracking and efficient navigation on uneven terrains [73], [194], [196], [199]-[204].

The incorporation of wheel-leg mechanisms markedly improves the efficiency of robot locomotion across a variety of terrains [21], [202], [206]-[208]. Innovative strategies, such as inverted equilibrium manifolds and advanced jump control algorithms, bolster the robots' balance and steering capabilities [202], [207], [209]. Moreover, these robots exemplify cutting-edge motion planning and control developments, including optimized crawling in tight spaces and the ability to account for real-world uncertainties during simulation testing [210], [211]. Bipedal robots that can adapt to varying ground conditions by blending walking and wheeling techniques show promise in achieving speed and energy efficiency across diverse applications [210], [212]. Unique design features, such as the three-degree-of-freedom (DOF) serial-parallel hybrid mechanism, demonstrate remarkable motion precision, highlighting their applicability in tasks requiring delicate movements [213].

Recent studies have explored the potential of leg mechanisms inspired by reptiles for their stability and agility [212], [214]. Investigations into balance control strategies for human-exoskeleton systems and the replication of agile walking behaviours seen in insects and crustaceans contribute valuable insights for potential applications in areas like rehabilitation, sports, and industrial automation [110]. Additionally, the emergence of metamorphic parallel leg mechanisms, capable of toggling between three and four degrees of freedom, affords these systems greater adaptability in unpredictable environments [111].

To optimize the future deployment of these bipedal wheel leg robots, refining their designs, fortifying control algorithms, and heightening energy efficiency are imperative [200], [215]. Table 7-Table 9 offer detailed perspectives on these facets, delineating advancements in stability balance control for bipedal wheel-leg robots and system design, control, motion planning, and control for these robots. Each table effectively collates the primary research emphasis and outlines implications for future endeavours, highlighting pivotal growth areas and potential impediments.

Within the riveting domain of robotics, bipedal wheel-legged robots represent the confluence of groundbreaking technology and pragmatic application. However, despite substantial strides made, several challenges persist that hinder the realization of their complete potential. These challenges encompass complex coordination of sprawling legs with wheels, ensuring lasting robustness and durability, and cultivating advanced perception competencies [216]-[219].

Upon closer examination of these challenges, the central issue arises—the precise control and seamless coordination of these robotic entities. This serves as a compelling foundation for future research, brimming with opportunities for exploration and innovation. Notably, two critical areas warrant attention: the enhancement of optimization techniques and sensor integration, both of which are instrumental in augmenting the robots' perception capabilities [42], [223], [227]-[229]. Furthermore, the exploration of machine learning and adaptive control techniques holds promise. These methodologies have the potential to facilitate smoother mode transitions, enabling these robots to adeptly adapt to diverse operational environments [198], [230]. Additionally, fostering collaboration between humans and robots can unveil new prospects for usability and performance optimization. The integration of soft and compliant mechanisms also presents a promising avenue [198], [230] . The incorporation of such elements can enhance the robots' adaptability and resilience, thereby enabling them to navigate diverse terrains and perform a multitude of tasks effectively.

Table 7. Advancements in Stability and Balance Control for Bipedal Wheel-Leg Robots

Focus	Synthesis	Implication for Future Research
Slope stability [220].	Develop streamlined control for precise slope stability in wheeled humanoid robots.	Explore advanced control techniques for improved slope stability.
Gait generation for damaged bipeds [221].	Develop stable gait generation methods for impaired biped robots: single control torque application and period-2 gait demonstration.	Investigate enhancing stability in damaged biped robots using reaction wheels and control adjustments.
Terrain Interaction [199].	Implement SMC and EPE methods for TWIP robot control on uneven terrain.	Improve TWIP robot stability on uneven terrain.
Balancing Rolling Condition [203].	Achieve stable short-range trajectory control in two-wheeled biped robots using a kinematic control model.	Enhance performance in numerical simulations and trajectory planning.
Inverted Equilibrium Manifold Balance [204].	Attain effective balance through configuration transformation on the Inverted Equilibrium Manifold for Wheel-Legged Robots.	Investigate advanced control for improved balance in changing configurations.
Linear and Nonlinear Controllers [201].	Develop dual balance control techniques for wheel-legged robots under various conditions.	Explore advanced algorithms and adaptive control for better balance control techniques.

Focus	Synthesis	Implication for Future Research
Control and Dynamic Characteristics [202].	Improve balance and motion control in wheeled legged robots.	Further research on enhancing control for versatile robot motion
Model Predictive Control [73].	Implement real-time control using linear center of mass dynamics to stabilize bipedal robots.	Investigate refinements in Model Predictive Control for enhanced stability.
Whole-body Dynamic Control [175].	Implement whole-body dynamic control for stabilizing two-wheeled humanoid robots.	Explore practical applications of this control technique
Model Predictive Control [98].	Improve balance control and navigation efficiency in complex environments.	Adapt the method for complex environments to assess its practical applicability.
Model Reference Adaptive Control [196].	Design and evaluate a Model Reference Adaptive Control (MRAC)-based stabilization system for two-wheeled robots, demonstrating stable operation and improved performance.	Test MRAC in diverse or challenging scenarios.
Intelligent Motion and Balance Controller [222].	Design a wheeled bipedal robot with an intelligent motion and balance controller based on fuzzy logic.	Apply the proposed IMBC system in controlling wheeled bipedal robots.
Balance-assist system [206].	Use a wheel-legged robot with an LQR controller as a balance-assist for individuals.	Include comprehensive motion planning for robot maneuvers.
Disturbance Observer Control [21].	Develop controllers with a compound disturbance observer for maintaining excellent control performance for a two-wheeled inverted robot.	Verify the controller's effectiveness in real-world scenarios.

Table 8. System Design and Control for Bipedal Wheel-Leg Robots

Focus	Synthesis	Implication for Future Research
Leg-wheeled system design [220].	Proposed biped leg-wheeled system with 3 locomotion modes, including stair negotiation.	Enhance efficiency on flat surfaces and stairs for improved versatility.
Bipedal leg-wheeled system [221].	Explored a feasible 6-DOF bipedal leg-wheeled robot with balancing and locomotion control.	Investigate wheeled humanoid robots for agility, speed, and energy efficiency enhancements.
Control Strategies [190].	Compared robust PI controllers and LQR for TWIPR control via simulations and practical tests.	Evaluate a new control scheme's effectiveness when compared to existing strategies.
Noise Reduction Techniques [192].	Developed a robust motion controller for wheeled biped robots using Extended Kalman Filter.	Pursue the development of a robust motion controller for real-world applications, focusing on noise reduction.
Jump Trajectory Computation [191].	Designed a control algorithm for balance, steering, and jump trajectory in bipedal wheeled robots.	Enhance robot control tools and trajectory design for improved performance.
Balancing at Desired Speed/Height [192].	Designed dynamics for a wheeled-legged robot with optimal control for balance at speed and height.	Develop a control unit to ensure balanced movement in various directions.
Decoupled Control Framework [193].	Designed a decoupled control framework for a wheeled biped robot with effective balance maintenance during configuration changes.	Address small location drift during configuration transformation.
Shared-Control Methods [194].	Investigated force feedback in shared-control methods for wheeled humanoid tele locomotion.	Optimize force feedback applications for both familiar and unfamiliar environments.
Hybrid Learning and Model-Based Controller [223].	Developed a Hybrid LMC for wheeled humanoid locomotion control with improved performance and increased sample efficiency.	Further investigate the effectiveness of Hybrid LMC for future applications.
Balance Control Using LQR [197].	Applied LQR for balance control of a wheel-legged robot through efficient simulation and experiments.	Optimize control strategies and explore motion planning for improved balance control in various scenarios.
Hybrid Control Scheme [224].	Created a hybrid control scheme combining adaptive controller with feedback LQR for balanced robot control.	Validate the L1 adaptive controller in real-world scenarios through testing and validation.
Compensation for Uncertainties and Disturbances [223].	Developed an augmented controller for wheeled robot stability that compensates for model uncertainties and external disturbances.	Conduct further validation through extensive simulations and real-world experiments.

Focus	Synthesis	Implication for Future Research
E-Jet Assistance in Balancing [195].	Designed a bipedal wheel-legged robot with E-Jet for enhanced balance and disturbance rejection.	Validate the technique under diverse real-world conditions.
Hybrid Wheel-legged Robot Design [122].	Successfully developed a hybrid wheel-legged robot for disaster rescue or field exploration with improved mobility and environmental adaptability.	Focus on enhancing the hydraulic system and overall control for practical applications.

Table 9. Motion Planning and Control for Bipedal Wheel-Leg Robots

Focus	Synthesis	Implication for Future Research
Jumping Techniques [198].	Developed a hierarchical scheme for improved jumping control in wheeled bipedal robots.	Enhance jumping control further within the hierarchical scheme.
Hybrid Locomotion [6].	Created a dynamic locomotion and obstacle avoidance framework for wheeled biped robots.	Improve dynamic motion planning and control for real-world use.
Jump Control [13].	Designed a hydraulic wheel-legged robot jump control algorithm for stable and gentle jumping.	Focus on further reducing landing shocks and pitch angle fluctuations.
Kinematic Control Model [6].	Developed a control model for effective self-balancing during robot configuration changes.	Address small location drift during configuration transformations.
Force-tracking Performance Framework [208].	Established a framework for hydraulic wheel-legged robots to navigate flat and rough terrains with self-balance achieved via kinematic control.	Validate reliable performance through real-world testing.
Locomotion Control via Quadratic Programming [201].	Implemented predictive control for 2-wheeled inverted pendulum robots with successful simulations.	Explore decomposing the robot for lower dimensional dynamics while maintaining equivalence to the full order model.
Transitioning Between Motion Modes [225].	Developed control strategies for motion mode transitions in wheel-legged robots with successful crawling motion control for low and narrow passages, verified through experiments.	Further optimize crawling mode in confined spaces.
Adaptive Motion Control Approach [210].	Introduced adaptive motion control for self-balancing leg-wheeled mobile robots, enhancing navigation and stability in various terrains.	Validate simulated results through additional experiments and real-world scenarios to improve robot performance.
Reinforcement Learning [223].	Demonstrated reinforcement learning algorithms outperforming traditional controllers in wheeled biped robot control.	Incorporate real-world uncertainties into simulations and assess algorithm robustness.
Uncertainty and Disturbance Estimation [137].	Proposed FL-UDE controller for improved wheel-legged robot movement control with UDE, feedforward compensation, and virtual model principles.	Investigate control strategy application in real-world scenarios and complex robotic systems.
Gait Generation [226].	Developed an efficient underactuated bipedal gait using a reaction wheel at the hip joint.	Further research needed to refine system parameter selection.
Whole-body Control Framework [211].	Successfully developed a whole-body control framework enhancing balance control and dexterity in wheel-bipedal robot Ollie.	Apply the technique to enhance dexterity in similar outdoor robots.

Table 10 offers a comprehensive overview of various aspects of terrain interaction concerning bipedal wheel-leg robots. It succinctly encapsulates the current research landscape and directs attention towards potential avenues for future studies. To bring things together, the evolution of bipedal wheel-legged robots represents a significant stride in the field of robotics. This advancement is characterized by continual improvements in design and control strategies, with a particular focus on enhancing stability, adaptability, and performance across diverse environments. Future research endeavors should prioritize the development of advanced control mechanisms, refined motion planning strategies, and the exploration of hybrid models that harness the strengths of both legged and wheeled locomotion. The interdisciplinary nature of this field, drawing insights from robotics, computer science, biomechanics, and materials science, promises exciting prospects for revolutionary applications in assistive technology, disaster response, and beyond.

Table 10. Terrain Interaction for Bipedal Wheel-Leg Robots

Focus	Synthesis	Implication for Future Research
Terrain-adaptive Control [226].	Designed a terrain-adaptive, self-balancing leg-wheeled robot with multiple control algorithms for autonomous navigation over rough terrain.	Validate controller effectiveness in real-world conditions through additional experiments.
Configuration Transformation [120].	Achieved stable and gentle jumping of a wheel-legged robot on the Inverted Equilibrium Manifold with reduced landing shocks.	Further explore and refine this novel jump control method for hydraulic robots.
Inverse Kinematics Model & Dynamic Control [211].	Improved terrain adaptability and attitude control for wheel-legged vehicles, enhancing balance and speed.	Investigate the control unit's capabilities for maintaining balance and speed in various directions.
Jump Control Algorithm [202].	Developed a jump control algorithm for hydraulic wheel-legged robots with effective balance, steering, and jump trajectory computation.	Focus on refining simulation tools for robot balance and jump trajectory computation.
Quasi-direct Drive Actuation [207].	Successfully designed a bipedal wheel-legged robot with proprioceptive quasi-direct drive (QDD) actuators capable of high-frequency force control.	Combine the LQR controller with whole-body control, develop jumping algorithms, and explore payload integration.
Multi-modal Locomotion [208].	Established an autonomous control framework for a bipedal robot to ride Hovershoes.	Integrate this framework with the robot's walking capabilities and develop autonomous robots with multi-modal locomotion.

8. Conclusion

In conclusion, bipedal wheel-leg robots are on the verge of transforming the realm of robotics and extending their impact to emergency response and industrial applications. Picture these robots navigating challenging landscapes like earthquake-ravaged cities or wildfire-damaged forests, diligently searching for survivors. While their adaptability across intricate terrains and seamless transitions between locomotion modes represent noteworthy achievements, there are still substantial hurdles to overcome in terms of sensor integration and control mechanisms. From an ethical perspective, the implications are profound. These robots have the capacity to handle hazardous tasks, such as managing toxic substances or defusing explosives, thus reducing human exposure to risk. Their role in assistive technologies that enhance mobility for individuals with disabilities signifies a significant step towards societal inclusivity. However, the path forward is rich with both opportunities and challenges. It involves not only achieving mechanical proficiency but also instilling cognitive adaptability. Hybrid designs that leverage both legged and wheeled movements offer an intriguing avenue for exploration. Advances in machine learning and control strategies will be pivotal in realizing their full potential, from navigating disaster-stricken areas strewn with debris to optimizing logistics in intelligent warehouses. The intricacies related to the design of these remarkable machines, the ethical considerations they raise, and their practical applications warrant continued exploration in the future. A balanced approach is crucial, where careful consideration is given to both the advantages and challenges posed by robotics to harness their potential for the greater good. Taking proactive steps by delving deeper, fostering innovation, and exploring this promising field is imperative.

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