Control and Gait Generation of Biped Robots: A Review

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Abstract.

This review paper explores the translation of human negotiation behaviours to bipedal walking robots, considering the inherent differences in morphology between humans and robots. Despite considerable advancements in bipedal robotics in recent years, mechanical bipeds still lack the agility and robustness exhibited by their biological counterparts, particularly in unfamiliar or dynamically changing environments. This limitation can be attributed to the absence of online motion planning, reflex-like control, and non-advantageous passive dynamics, which biological systems employ to effectively overcome disturbances, especially when encountering significant unplanned changes in stepping height.

Keywords: bipedal walking robots, gait generation, control.

1 Introduction

Efficient operation of biped robots in everyday environments necessitates the development of suitable locomotion algorithms capable of addressing the inherent challenges of balancing on two feet and managing multiple contacts. Recent advances in balancing approaches have focused on achieving whole-body control, which treats the problems of balancing, interaction, and environmental manipulation as an interconnected challenge. Common strategies for whole-body control can be broadly categorized into two groups based on the methodology employed to generate control signals: solving inverse kinematics/dynamics of the robot or utilizing passivity-based approaches. Traditional walking approaches for biped robots typically involve motions that maintain flat foot-ground contact. However, various alternative approaches have been proposed to emulate human gait on biped robots, incorporating phases such as stretched knees, heel-strike, and toe push-off motions to achieve energy-efficient locomotion, akin to human gait patterns.

2.1 Locomotion of a biped robot

Biped robots, characterized by their two legs, have the capability to walk on various surface and perform tasks similar to those carried out by humans. The locomotion of biped robots is significantly influenced by the gait cycle and the environmental structure in which they operate. The gait of a biped robot refers to the coordination between its legs and body movements during locomotion on specific surface. It can be classified into periodic and non-periodic gaits. Periodic gaits involve the repetitive generation of the same sequence of steps from start to finish. Non-periodic gaits, however, adapt their gait cycle based on environmental conditions. The walking cycle of a biped robot consists of two distinct phases: the single support phase (SSP) and the instantaneous double support phase (DSP). During the SSP, the robot takes a forward stride and covers a certain distance, while the DSP is a momentary phase that allows for the exchange of leg support. Gait generation for biped robots can be achieved through two approaches: active walking and passive walking. Active walking involves attaching actuators to the joints of the robot's models, enabling controlled movements. In contrast, passive walking does not involve actuators and relies on natural dynamics and momentum [1]. Two main types of bipedal walking systems are static walking and dynamic walking. In static walking, the balance of the biped robot is determined based on the center of mass (COM). On the other hand, dynamic walking involves a faster walking cycle compared to static walking, with the balance of the biped robot assessed based on the zero-moment point (ZMP). The ZMP represents the point around which the sum of all moments generated by active forces equals zero. The balance of a biped robot can be measured using the concept of dynamic balance margin (DBM), which evaluates the robot's ability to maintain stability during walking. The introduction of the concept of Zero Moment Point (ZMP) by researchers

Vukobratovic and Stepanenko [2] has played a significant role in gait generation for biped robots. They considered the upper body of the biped walking model as an inverted pendulum, with the ZMP aiding in the determination of the Dynamic Balance Margin (DBM). The DBM provides an estimation of the robot's stability in dynamically balanced systems. Various techniques have been employed to compensate for the ZMP and ensure stability, including preview control, AI-based gait generation, and model predictive control. Additionally, researchers have explored periodicity-based gait, capture point theory, and foot placement estimators to analyze dynamic stability in biped robots [3].

Overview of the gait generation techniques

There are four primary techniques for generating different types of gaits: 1-model-based, 2-natural dynamics-based, 3-bionic kinematics or biological mechanism-based, and 4-stability criterion-based approaches [4]. The model-based technique primarily relies on interpolation to create reference trajectories by satisfying constraints using polynomial functions. These trajectories are then followed using control mechanisms. Another model-based approach involves modeling the dynamics of a linear inverted pendulum (LIPM) and optimizing gaits considering variables like energy consumption, robot construction, control systems, and adaptability. However, a drawback of this technique is that it necessitates extensive knowledge of the dynamic parameters specific to the bipedal model being used. It should be acknowledged that the generation of gaits inspired by biological mechanisms draws from motion capture data of humans, allowing for the creation of stable rhythmic patterns that can be rapidly modified in terms of pattern and speed. Central pattern generators (CPGs) and neural networks (NN) located within the spinal cord play a significant role in generating rhythmic locomotion without reliance on sensory signals. Two widely used models for CPGs are the Matsuoka neural oscillator and the Van der Pol oscillator. Additionally, other biologically inspired approaches fall under the realm of artificial intelligence (AI)-based gait, incorporating genetic algorithms (GA), fuzzy logic (FL), and NN [5].

Fundamental aspects of modelling a biped robot entail determining the number of degrees of freedom, including the allocation and orientations of the actuators. Furthermore, trajectory planning must be considered for each component of the robot's mechanism, such as the swing foot, wrist end, and hip, to enable the robot to navigate from its starting position to the desired destination. Analytical modeling can focus solely on trajectory planning in the sagittal plane, while 3D modeling involving the sagittal, frontal, and horizontal planes is necessary for the robot to walk in a real environment. Researchers have also examined various walking patterns, foot and ground contact types, the impact forces generated by the heel striking the ground, and the arrangement of heel and toe contact with the ground, all aimed at enhancing stability robustness [6]. Moreover, the flexibility of elastic and stiff links within the robot can help absorb impacts but may introduce instability due to uncertain motions caused by elasticity. The mobility of the links is contingent upon active or passive joints. Various stability criteria, such as ZMP, CoP, COG, and FRI, can be adopted based on the specific skills required, Consequently, the mathematical model of a biped robot encompasses kinematics and dynamics, which can be implemented using high-level programming languages. Researchers can also employ software tools like CoppeliaSim, ROS, Gazebo and MATLAB to simulate and verify the feasibility of their planned models. There are several important considerations for gait generation of biped robots on any surfaces. These include balancing, control, trajectory synthesis, and foot-ground interaction. Various methodologies have been developed by researchers, and we will discuss four fundamental gait generation techniques commonly used:

1. Central Pattern Generators (CPGs): CPGs are biological-inspired oscillatory networks that generate rhythmic patterns of motion. They are commonly used for generating walking gaits in biped robots. CPGs produce coordinated joint trajectories by controlling the timing and amplitude of oscillatory signals.

2. Zero Moment Point (ZMP) Based Approaches: ZMP is a concept used in humanoid robotics for maintaining dynamic stability during walking. ZMP-based approaches involve calculating the ZMP location and generating footstep trajectories to keep the ZMP within the support polygon. These approaches focus on maintaining balance and stability throughout the gait cycle.

3. Passive Dynamic Walking: Passive dynamic walking exploits the inherent dynamics of the biped robot to achieve energy-efficient walking. By carefully designing the mechanical structure and ensuring proper passive dynamics, the robot can generate walking motions without active control. This approach relies on gravity and the natural dynamics of the system for gait generation.

4. Optimization-Based Methods: Optimization-based methods involve formulating the gait generation problem as an optimization task. The objective is to find optimal control inputs or trajectories that satisfy certain criteria, such as energy efficiency or stability. These methods use mathematical optimization techniques to find the best solution within given constraints.

These gait generation techniques provide different approaches to achieve stable and coordinated walking on a flat surface. Researchers choose the most suitable method based on the specific requirements of the robot and the desired walking behaviour. By addressing issues related to balancing, control, trajectory synthesis, and foot-ground interaction, these techniques contribute to the development of efficient and stable bipedal locomotion on flat surface [7].

Overview of the Control Techniques

Numerous researchers have dedicated their efforts to developing diverse control algorithms aimed at effectively managing the motions and dynamic balancing of biped robots, ensuring smooth coordination among the various motors in each joint. In this section, there are several popular control techniques, including:

1-The PID (proportional integral derivative) controller is widely recognized and extensively utilized in industrial applications. It comprises three components: the proportional, integral, and derivative gains, which calculate the errors between desired and actual values. The simplicity and ease of control over the gains have made PID controllers a popular choice in the field of robotics. To address nonlinearities in the system, the PID controller can be simplified as PI (proportional integral), PD (proportional derivative), or ID (integral derivative) controllers. PD-based tracking systems exhibit adaptivity to system parameter variations and external forces. However, it is important to note that when the uncertainty level exceeds 80%, the PID controller may fail to generate stable gaits for walking on flat terrain and stairs during the single support and biped-in-air phases. The constant gain of the PID controller initially leads to high-speed performance, which gradually decreases, while the adaptive gain of the PID controller ensures smoother operation of the biped robot. To control the convergence rate of tracking errors during the continuous swing leg task and mitigate nonlinear impacts during discrete foot-ground contact, a PD controller is employed. The hybrid zero dynamics (HZD) assumptions are utilized for foot impact assignment [8].

2-The Computed Torque Controller (CTC) is an effective approach for generating dynamically stable gaits while mitigating the nonlinearities within the system. However, it requires an accurate dynamic model of the robot mechanism, which imposes limitations on its applicability. CTC is often referred to as an inverse dynamics controller and is widely utilized in various applications. CTC operates based on the principle of feedback linearization, which involves transforming a nonlinear model into a linear one. By calculating and eliminating all nonlinearities and cross-coupling terms, the system can be simplified and stabilized. This approach allows researchers to use linear controllers such as PD and PID controllers to control nonlinear systems. However, accurate dynamical models of robotic manipulators are required for the CTC scheme, which restricts its usage. By utilizing CTC and integrating it with other control techniques, researchers aim to enhance the trajectory tracking capabilities of robotic manipulators and deal with uncertainties, ultimately improving the performance and adaptability of the control system [9].

3-The Neural Network (NN) technique is employed to achieve closed-loop execution and effectively control bounded errors. NNs possess both offline and online real-time learning capabilities, making them easily implementable. In many approaches, the NN-based controller is integrated with the Cerebellar Model Articulation Controller (CMAC). CMAC is a memory based NN. It has found applications in robotic systems, particularly in reinforcement learning architectures. CMAC employs associative memory, simplifying the challenges associated with large-scale NNs. It exhibits improved learning speed, computational simplicity, and ease of implementation compared to conventional NNs. The integration of NNs and CMAC provides a powerful framework for developing robust and adaptive control systems, enabling robots to learn and adapt to changing environments. By leveraging the memory-based and associative properties of CMAC, the NN-based controller can effectively address complex control tasks while maintaining efficient computation [10].

4-The Fuzzy Logic Controller (FLC) is a control scheme that examines input parameters and treats them as linguistic data ranging from 0 to 1, representing false and true values, respectively. Unlike traditional binary logic, FLC assigns partial truth values within the range of 0 to 1, allowing for the representation of partial accuracy. Unlike conventional control techniques, FLC does not rely on precise mathematical models or perfectly designed inputs, making it particularly useful for mitigating nonlinearities. The advantage of FLC lies in its ability to handle complex control tasks where exact mathematical modeling is challenging or infeasible. By utilizing linguistic variables and fuzzy rules, FLC can effectively capture and represent the imprecise nature of real-world systems. This allows FLC to reduce nonlinearities and achieve satisfactory control performance even without relying on precise models or inputs [11].

5-The Impedance Controller is a dynamic control approach that focuses on regulating the force and position of the robot's links. Its primary objective is to control the impedance, which refers to the force exerted by the environment in response to the robot's movements. This controller is widely used in robotics to ensure dynamic stability and robustness during various gaits and tasks. It utilizes a feedback control algorithm to impose a desired Cartesian impedance on the end effector of a nonlinear manipulator. This approach allows for the control of the robot's behavior in relation to its surrounding environment. Unlike traditional control methods that require solving inverse kinematics problems, the impedance controller offers a more straightforward and effective way to regulate robot motion. One of the notable advantages of the impedance controller is its versatility in handling different control actions to accomplish diverse tasks. By superimposing various controller actions, the researcher can tailor the robot's behavior to specific objectives [12].

6-Model Predictive Control (MPC) is a comprehensive control strategy that aims to satisfy system constraints and optimize system responses. It is widely used in various fields, including robotics. The key idea behind MPC is to provide reference trajectories based on which the future behavior of the system is predicted. Although MPC imposes a significant computational load, it offers advantages over structured PID controllers, particularly in terms of robust control against system parameter changes. It is also well-suited for complex multivariable processes. MPC operates by evaluating the current system state and predicting the future response of the system. Based on this prediction, it calculates the optimal control actions by solving a dynamic optimization problem, while considering input and state constraints at each sampling time. The architecture of MPC relies on an integrated linear or nonlinear model that captures the dynamic behavior of the process. One of the key features of MPC is its ability to handle complex multivariate process control systems. By considering the anticipated process responses and current state evaluations, MPC calculates the best control trajectory to optimize system performance while respecting constraints. This makes MPC suitable for sophisticated control tasks where multiple variables need to be controlled simultaneously [13].

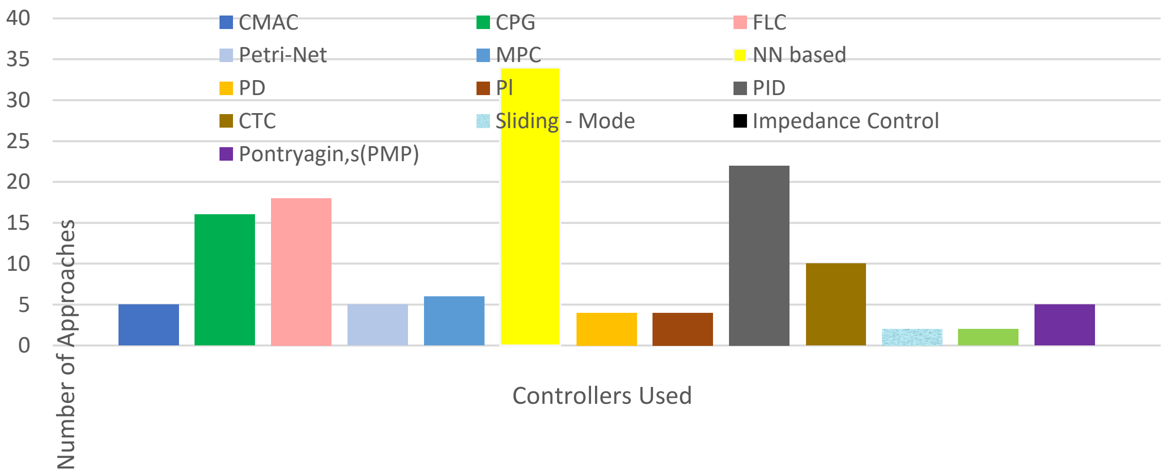

Fig.1. Number of different control methods used in all Gait Generation techniques

Gait generation on a flat surface

Most of the researchers adopted the model-based gait technique for walking on flat surface, which is the simplest case compared to any other surfaces. Researchers have adopted various techniques for gait generation on flat terrain for biped robots. These techniques include model-based approaches, control schemes to handle nonlinearities, optimization-based methods, physics-based gait generation, stability criterion-based gait, and bionic or biological mechanism-based gaits. Here is a summary of the different approaches mentioned:

1. Model-Based Approaches: Researchers have used various dynamics models such as LIPM, virtual height inverted pendulum mode, Euler-Lagrange formulation, Newton-Euler approach, and forward and inverse kinematics to model the biped robot and generate gait trajectories. These approaches involve calculating joint reference trajectories, often using polynomial functions, to achieve desired walking behaviour [14].

2. Control Schemes for Nonlinearities: Several control schemes have been developed to handle the nonlinear dynamics of biped robots. These include feedback control techniques, eigen structure assignment, two-level control schemes, robust control techniques, local feedback at each joint, and feedback control schemes for stable cyclic gait. These control schemes aim to ensure dynamic stability and reduce deviations in the walking motion [15].
3. Optimization-Based Methods: Optimization techniques, such as Hamilton-Jacobi-Bellman equations, have been used to optimize energy consumption and find optimal periodic gaits. These methods consider energy efficiency and other criteria while generating gait trajectories [16].
4. Physics-Based Gait Generation: Some researchers have focused on exploiting the natural dynamics of the biped robot to achieve gait generation. This includes passive pendular gaits, inverted pendulum-based biped robots with virtual springs and dampers, and intuitive gait strategies based on forces and posture [17].
5. Stability Criterion-Based Gait: Stability criterion-based approaches involve generating gait trajectories based on stability criteria such as ZMP (Zero Moment Point) trajectories. These approaches aim to ensure stability and balance during walking by controlling the robot's center of gravity and foot-ground interactions [18].
6. Bionic or Biological Mechanism-Based Gaits: Inspired by biological mechanisms, researchers have developed gait generation techniques using concepts like biorhythm-based controllers, bi-layer controllers, and nonlinear oscillators. These approaches mimic biological principles and utilize sensory information to generate stable and rhythmic walking motions [19].

Each approach has its advantages and limitations, and researchers choose the most appropriate technique based on the specific requirements of the biped robot and the desired gait behaviour. These techniques contribute to the development of efficient and stable walking gaits on flat surface.

Gait generation on ascending and descending the sloping surfaces

Gait generation of the biped robot on a sloping surface is a more challenging task than the flat surface. Indeed, model-based gait generation approaches for ascending and descending sloping terrain are relatively less common compared to flat surface. Stability criterion-based approaches have been explored for gait generation on slopes as well. Biological mechanism-based gait approaches have also been explored for ascending and descending sloping terrain. The central pattern generator (CPG) has inspired researchers to develop learning architectures for biped robots, enabling autonomous bipedal gait. Smooth gait transitions between flat and sloping surface have been achieved, as well as stable gait on unknown inclinations and adaptivity in different environments. AI techniques, such as Genetic Algorithms, neurons and neural pathways, genetic-neural (GA-NN) and genetic-fuzzy (GA-FLC) approaches, and integration of neural networks (NN) with modified chaotic invasive weed optimization (MCIWO) and particle swarm optimization (PSO) algorithms, have been employed to generate complex gait patterns [20]. These approaches have enhanced the efficiency of biped robots walking on sloping surface. However, when there is a change or increase in the slope angle, additional sensors, such as position sensors, force sensors, gyroscopes, accelerometers, and inertial measurement units (IMUs), are necessary to detect and adapt to the slope gradient and upper body posture. To overcome the complexity of mathematical modeling, a collective balancing reflex incorporating threshold, PID, and hybrid control has been developed using a 2-axes accelerometer sensor. With the increased complexity of sloping terrain, researchers have turned to advanced AI-based and bionic gait generation techniques to improve adaptivity. By drawing inspiration from biological mechanisms and utilizing stability criteria, they have made significant progress in generating bipedal gait on slopes. These approaches leverage the principles of human locomotion and stability to design effective gait patterns for navigating sloping terrain. The integration of AI techniques, such as central pattern generators, genetic algorithms, neural networks, and optimization algorithms, has further enhanced the adaptability and efficiency of biped robots on sloping surfaces. By combining the understanding of biological mechanisms with AI-based methods, researchers have been able to develop more robust and adaptive gait generation algorithms for traversing sloping surface [21].

Gait generation on ascending and descending the staircase

Gait generation on staircases presents unique challenges compared to flat or sloping surfaces. The relationship between the dimensions of the steps and the robot's leg length becomes crucial, as any miscalculation can result in collisions with the staircase. In this context, the mechanism for initiating the swing phase and determining the characteristics of the gait pattern, particularly the take-off phase, becomes essential. To ensure stability, it is crucial to synchronize all robot links and define proper foot trajectories. The gait generation process must account for the specific requirements of ascending and descending stairs. These gait patterns involve controlling the forward speed of the gait and accurately placing the swing foot to navigate the stairs effectively. By carefully managing the swing phase and foot placement, the robot can maintain stability and successfully traverse staircases. Several researchers have achieved stability in bipedal locomotion through different methods. Also, the integration of bionic gaits and AI-based techniques has enabled researchers to generate adaptive and autonomous gaits [22].

Gait generation for avoiding, crossing, and stepping over the obstacles

The goal of advancing biped locomotion is to develop a highly capable humanoid robot capable of mimicking human motions. However, replicating the sensory and intuitive knowledge inherent in humans poses a significant challenge. To imbue humanoid robots with a sense of intuition, researchers have explored the application of reinforcement learning (RL) algorithms, leading to the proposal of unique methodologies. While many researchers have focused on path planning to navigate around obstacles, only a few have delved into the task of identifying obstacles and successfully crossing or stepping over them. In addition, many navigation approaches rely on artificial intelligence (AI) techniques to identify obstacles and navigate around them for obstacle avoidance [23].

Gait generation for avoiding the dynamic obstacles

Numerous studies have focused on addressing obstacles encountered by biped robots during their locomotion. While existing techniques and frameworks have proven effective in handling stationary or static obstacles, they often overlook the presence of moving or dynamic obstacles, which are more representative of real-world walking scenarios. To address this limitation, an integrated algorithm called DWA-TLBO (Dynamic-Window Approach and Teaching Learning Based Optimization) been proposed. This algorithm takes into account the positioning of both the target and the obstacles, using it as input to optimize the speed and intermediate steps through the Dynamic Window Approach (DWA), while the Teaching Learning Based Optimization (TLBO) algorithm collectively evaluates the optimal turning angle to avoid the obstacles [24]. Indeed, the proposed approach described in the research can contribute to the development of a fast and robust architecture for humanoid robots to navigate and interact in real environments, emulating human-like behavior. However, it's important to note that relying solely on networked communication for identifying safe routes and avoiding collisions may not be feasible in every scenario, as not everything in the natural environment can be networked. To address this challenge, object detection techniques utilizing visual sensors and reinforcement learning (RL) algorithms come into play. Visual sensors, such as cameras, provide valuable information about the robot's surroundings, allowing it to perceive and recognize objects in real-time. By employing object detection algorithms, the humanoid robot can identify obstacles, navigate around them, and make informed decisions to ensure safe and efficient movement [25]. Furthermore, reinforcement learning algorithms can enhance the robot's ability to learn from interactions with its environment. By employing RL, the humanoid robot can continuously improve its decision-making processes and adapt its navigation strategies based on feedback and experiences. This enables the robot to operate in real-time environments, learn from dynamic situations, and make intelligent choices to navigate effectively and avoid collisions.By combining visual sensors, object detection techniques, and RL algorithms, humanoid robots can function autonomously and adaptively in real-world environments, mimicking human-like perception and decision-making capabilities.

Gait generation for crossing over the ditches

The research on gait generation for crossing ditches has been limited, but a few notable studies have explored this area. A gait planner been proposed for ditch crossing using analytical modeling, neural network (NN), and fuzzy logic (FL) optimization techniques. The gait planner aims to optimize dynamic balance margin and energy consumption for a 7-DOF biped robot. The NN and FL-based gait planners are trained offline using genetic algorithms (GA) to enable optimal online gait generation. These approaches, compared to analytical modeling alone, offer greater adaptability and balance with reduced energy consumption [26].

Gait generation on the uneven surface

The modeling of locomotion on uneven terrain is a challenging task due to the uncertainties and lack of specific patterns associated with such surface. Researchers worldwide have proposed various approaches to address this challenge and maintain dynamic balance for biped robots walking on uneven or rough terrain. Some of the notable approaches and techniques include:

1. LIPM-based biped models: Researchers have developed models based on the Linear Inverted Pendulum Model (LIPM) for biped robots with massless legs, simplified models for humanoid robots with ZMP delay and 3D LIPM-based models [27].

2. Adaptive algorithms and control techniques: Algorithms have been developed to accommodate deviations in speed and step length, inherit human walking behavior using a moving horizon technique, utilize ultrasonic reach sensors for walk control, and regulate foot impact on the ground for stable periodic gait [28].

3. Intuitive dynamics and controllers: Algorithms based on intuitive natural dynamics have been developed for biped robots. Controllers have been designed to navigate rough and irregular surface by arranging lower-dimensional directions and balancing linearized elements. Passive gait models based on open-loop sinusoidal oscillations of hip actuators have also been explored [29].

4. Intelligence-based gait generation: Hybrid intelligence methodologies using fuzzy NN controllers have been proposed for mobile robots to improve their learning speed and control in unknown environments. Schemes for modeling and tracking rough surface using RGB-D and IMU sensors have been developed for proper foot placement [30].

5. Stability and trajectory generation: Trajectory generation techniques utilizing stability constraints and Model Predictive Control (MPC) have been applied to generate online trajectories for Center of Mass (CoM) and Zero Moment Point (ZMP) for biped robots [31].

These approaches collectively address the challenges of locomotion on uneven terrain and the navigation of unknown environments. They improve the robustness and adaptability of biped gaits in real-world scenarios.

Gait generation in the unknown environment

When modeling and mapping the exact perspective of the unknown or uncertain environment, it becomes difficult for a biped robot to make a quick decision based on observational and sensory data collected by various sensors and devices. The robot must have a quick decision-making framework that makes it an intelligence-inbuilt mechanism. That is, more advanced technologies are required for doing so. Along with the decision policy, its controller also needs to perform the basic controlling operations for maintaining the dynamic balancing instantaneously. In comparing the various perspectives of intelligence in robotics and mechatronics, it can be said that animals are adaptable to their environments, and humans make some changes in the environment for comfort That means basic intelligence is all about being adaptive to the dynamic environment and making some improvements in the environment is advanced intelligence [32]. In the context of developing intelligent and adaptive biped robots, researchers have explored various techniques and perspectives. Here are some notable approaches:

1. Knee joint bending and hip height: Studies have shown that the torque consumption in the knee joint is influenced by factors such as the vertical distances between the ground and hip joint, and the length of the shank and thigh. The hip height is crucial for stability, optimal actuator torques, and deriving modified motion of the lower torso.

2. Foot mechanism and landing surface: Researchers have designed foot mechanisms to evaluate the relative position of foot support with respect to the landing surface and ground inclination.

3. Reinforcement Learning (RL) and training modules: RL techniques and training modules have been employed to incorporate intelligence and intuitive inheritance in bipedal walking robots. For example, inherited data from human locomotion were implemented in an RBFNN algorithm for generating real-time gaits. RL CPG actor-critic methods have been applied with policy gradient algorithms. Novel CPGs with bounded output oscillatory coherent networks have been proposed.

4. Mathematical modeling and trajectory evaluation: Mathematical models have been developed to evaluate trajectories of biped robots on different surface, considering the effects of hip height on torso motion.

5. Navigation frameworks and sensory systems: Navigation frameworks have been designed for humanoid robots, including mapping the environment, setting primitives, and obstacle avoidance. Real-time terrain realization sensory systems have been developed using SVM algorithms.

Researchers have found that reinforcement learning, neural networks, CPGs, environment mapping, and sensor-based systems have played a significant role in enabling biped robots to walk in unknown environments and make adaptive decisions. These approaches aim to enhance the intelligence and adaptability of biped robots, allowing them to operate effectively in dynamic and uncertain surroundings [33]. Here is a breakdown of the different categories you mentioned:

1. Model-based gait generation: This approach involves optimizing gait parameters, reference trajectories, and using the Linear Inverted Pendulum Model (LIPM) dynamics. It requires a precise dynamic model of the robot and is considered more traditional and fundamental.

2. Biological mechanism-based gait generation: Inspired by natural biological evolution, this approach does not rely on a precise dynamic model. It utilizes algorithms that mimic evolutionary processes to generate gaits.

3. Stability criterion-based gait generation: These techniques focus on ensuring stability and balance during gait generation. They consider stability criteria and constraints to derive optimal gaits.

4. Natural dynamics-based gait generation: This approach aims to replicate the natural dynamics observed in human walking. It focuses on capturing the inherent dynamics of walking and incorporating them into the gait generation process.

Many researchers have indeed shown interest in biological mechanism-based gait generation techniques, as they offer the potential to create adaptive and robust gaits without relying on precise dynamic models. However, it's important to note that different approaches have their own advantages and limitations, and researchers often combine multiple techniques to achieve optimal gaits while minimizing computational complexity [34]. Overall, the field of gait generation in biped robots is diverse, and researchers continue to explore and combine different approaches to improve the adaptability, stability, and robustness of biped locomotion in various environments. It is also good to mention that the controllers and intelligent algorithms utilized in gait generation for biped robots vary depending on the specific research approach and application [35].

Conclusion

The findings from this article can be summarized as follows:

1. Lack of systematic methodology and common evaluation practices: Due to the diversity of gait generation techniques, robot designs, degrees of freedom, power sources, and controllers, there is no standardized approach for comparing different methods. The choice of gait generation technique depends on the specific application domain, terrain conditions, and scenario.

2. Unique characteristics of biped robots and terrains: Due to the uniqueness of each biped robot and terrain, it is challenging to directly compare results from different approaches. Developing unified solutions is difficult in the interdisciplinary field of biped robots. Researchers should choose an approach based on available resources and skills. There is a need for a universal approach that can design and modify the properties of biped robots for predicting gait, velocity, acceleration, torque, power consumption, DH parameters, and construction cost.

3. Progress towards imitating human motion: While various algorithms have been developed for gait generation on different terrains, the research is still far from exactly imitating human motion. Only a few approaches have shown significant development in this aspect.

4. Complex problems and real-time constraints: Researchers should address complex problems by considering real-time constraints, obstacles, and the environment's functioning, similar to human beings.

5. Importance of center of mass and ZMP: Gait generation for biped robots is based on the concept of center of mass and Zero Moment Point (ZMP). Forward and inverse kinematics, polynomial curves, and dynamics calculations are essential for smooth gait generation on various terrains. Controllers such as

PI, PD, PID, sliding mode, observer-based, GA, PSO, DE, IWO, MCIWO, NN, and FLC have been used, with non-traditional controllers performing better on various terrains.

6. Navigation and obstacle avoidance: Generating a map of the environment and utilizing vision-based algorithms have been suggested for the navigation strategy of biped robots, using techniques such as topological mapping or visual odometry with RGB-D cameras.

7. Bipedal walking robots require sensor systems for body orientation, foot sole, force, touch, vision, and audio, enabling both movement and environmental interaction.

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