

To what extent can bipedal robots adapt to complex environments?

Ruilin Wang

Shanghai Pinghe School, Shanghai, China

leowang422@163.com

Abstract. Nowadays, the adaptability of bipedal robots to different terrains becomes a critical topic because the application environments of robots often are complex, variable, and often unstructured. Examining this adaptability not only reveals the current progress of gait control and perception methods but also highlights key challenges that must be addressed to enable reliable, real-world deployment of bipedal robotic systems. This essay will first introduce the mechanism, types, and controlling methods of bipedal robots then provide numerous popular robots and finally discuss some highly controversial discussions. Overall, after widely searching for different types of newly invented bipedal robots, a significant progress was seen in bipedal robot's adaptability when meeting distinct uneven terrains, which most of the bipedal robots showed strong adaptability to uneven terrains. This conclusion is crucial because it demonstrates the readiness of bipedal robots for real-world environments, where surfaces are often rarely flat or predictable. After improving the advancement of robot's adaptability, a safer and more effective applications in areas such as post-disaster rescue and exploration work.

Keywords: bipedal robots, terrain adaptability, gait control, compliant structures, complex environments

1. Introduction

Attempts at building walking machines can be traced back at least to the 1960s. In addition to research concerning bipedal robots, efforts were also made to develop monopedal [1] and quadrupedal robots [2]. One of the first functioning bipedal robots was developed in the 1970s by Kato [3]. Nowadays, with the support of highly developed technologies, robots are not only getting more popular and advanced but also gain tremendous attention from both companies and countries. "Robots have the potential to greatly improve the quality of our lives at home, at work, and at play" [4]. People gradually learned the importance of robots, as they can not only help facilitate people's lives while providing them with various kinds of convenience, but also provide crucial assistance in different situations. "Day by day, biped robots' usage is increasing enormously in all industrial and non-industrial applications due to their ability to move in any unstructured environment" [5]. Unstructured terrains are terrains that experienced deformation and has different roughness when walking through it, this changes the adaptability of bipedal robots when walking through them. However, with the improvements generated on adaptability and stability of bipedal robots, it can truly provide us with various kinds of advantages. *"Recent advances in legged locomotion have enabled quadrupeds to walk*

on challenging terrains. However, bipedal robots are inherently more unstable and hence it's harder to design walking controllers for them" [6]. Although there are several new advanced technologies to help partly deal with the problem of adaptability, there are still problems which have to be solved to improve the stability of bipedal robots due to their unique construction, which may probably result in bipedal robots' efficiency and safety.

Currently, both scientists and inventors have tried numerous kinds of ways to improve the adaptability of bipedal robots when they are working in complex terrains. Wu from university of Washington used a framework for the automatic synthesis of biped locomotion controllers that adapt to uneven terrain at run-time [7]. This framework synthesizes adaptive biped locomotion controllers for uneven terrain through footstep planning and real-time torque optimization. Moreover, Ngamkajornwiwat et al. present a continuous, online, and self-adaptive locomotion control inspired by biological control systems, including neural control and hormone systems which provide greater success and higher performance than other techniques when bipedal robots are walking on all terrains [8]. Liu et al. from University of New South Wales and his research team investigated an in-situ transformation method for a wheel-biped robot, using a projection-based algorithm to maintain balance during shape-shifting between walking and rolling modes [9]. In conclusion, the possible solutions of solving the adaptability of bipedal robots to different terrains are mainly related to locomotion control, including neural control and hormone system by adjusting the parameter to increase stability, by changing the configuration of the robots and so on, although some problems have yet been solved, there are still lots of obstacles waiting to be overcome.

This essay will mainly focus on research status, reasons which lead to an improving high level of adaptability. This essay will also discuss both the advantages and disadvantages of the improvements and summarize the research findings achieved by scientists and inventors and list the problems which may still have a significant impact on the development of bipedal robots.

2. Research review

2.1. Bipedal robots

2.1.1. Mechanism

"The kinematic structure is the defining feature of all bipedal robots" [10]. Wheeled robots, legged robots, or leg-wheeled robots had distinct kinematic structure, which means the mechanism for bipedal robots varies. Nowadays, as robot-related technologies had been improved significantly, new types of robots such as legged, humanoid robots were invented. This dramatically upgrades the performance of bipedal robots.

According to Figure 1(a), this is a typical robot-designing mechanism. The main advantage of this bipedal robot is that it simulates the mechanism of human legs, which a contracted design of mechanical structures and control systems is displayed. Most of their legs are composed of a hip to simulate a spherical joint like human, this gives the legs greater freedom of movement, allowing the robot to move in all directions, which greatly improved the mobility of robots' legs. Rotary actuators are used in this leg structure. They are mounted directly at the joints. This means that those leg components which are positioned closer to the origin of the serial chain are required to bear the weight of actuators and associated components located further downstream. However, this could cause the accumulation of backlash or elastic deformation from each individual joint while there is also a noticeable increase in the inertia of the robotic leg. Both factors could lead to severe inaccuracies of legs' positions, which is an obstacle of this joint-leg structure. Generally, through the joint mechanism of bipedal robots, bipedal robots are allowed to move more freely, which means they are

likely to adjust its gait more effectively when meeting softness or deformation of terrains, and briefly enhanced their adaptability to different terrains.

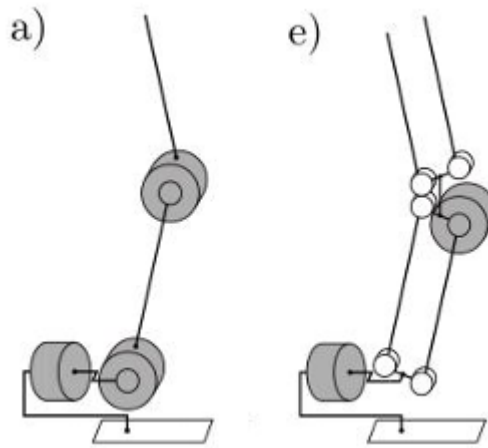


Figure 1. First part a in the picture represents a serial joint driven by servo motors. Second part in the picture represents a five-degree-of-freedom (5-DoF) serial-parallel leg configuration [10]

Moreover, by analogy, this characteristic can be leveraged in the mechanical component of the system, which also contributes to the bipedal robots' structural design. The NimbRo-OP2(X) robots [11, 12] utilize a five-degree-of-freedom (5-DoF) serial-parallel leg configuration, which integrates two 4-bar linkages in the sagittal plane and a serial chain dedicated to lateral movement (see Figure 1(e)). These 4-bar pantograph mechanisms restrict the leg's orientation, thereby maintaining the foot in a position parallel to the robot's waist. In the absence of tilting, the feet essentially retain parallelism with the ground. Notably, its actuation strategy differs fundamentally from conventional designs: instead of driving the hip and knee joints directly, the system adjusts the angles of the thigh and shank segments. The controlled orientation of legs but more flexible angle adjustment between leg parts enables the robot to better adapt to terrains.

To summarize, the kinematic structure of robots is a key determinant. Currently, the structure of humanoid robots is significant, researchers often use hips to simulate a spherical joint, which can produce similar functions as human's legs. At the same time, there are also scientists who designed a hybrid serial-parallel leg, this significantly reduces leg inertia and in turn the required joint velocities and torques, which are also more uniform. These robot mechanism help to enhance the adaptability of bipedal robots to different terrains.

2.1.2. Type

2.1.2.1. Wheeled robots

Wheeled robots are robots which use wheels as their actuating device, they use wheels to finish series of works. Wheeled robots' actuating mechanism is relatively simpler than legged robots because they usually work with repeated and simple gaits. Also, the continuous contact of wheels with the ground provides inherent stability and smoother trajectories. As a result, most wheeled robots are good at moving on paved and structured surfaces as they are able to move extremely fast and effectively on these surfaces. The key to keeping the robot moving is to ensure a continuous and stable rotation of the wheels. As shown in Figure 2, this is an imagery of wheeled robot, the wheels are connected to the robot's body, the movements of the two wheels drive the entire robot to move. Based on wheeled robots' gymnastic gait, wheeled robots' locomotion required less energy compared to legged movement despite less rolling friction is produced. Another advantage is that wheeled robots have fewer moving parts than legged robots, which means they can reduce

mechanical complexity, manufacturing costs, and maintenance requirements. However, wheeled robots often have limited terrain adaptability as they will struggle with irregular or soft terrains such as stairs, rocks, or uneven ground. Soft and deformable surfaces such as sand, mud, or grass made them easy to lose traction or become stuck.

In conclusion, wheeled robots generally have a higher efficiency on smooth surfaces and have a relatively lower manufacturing cost than other robots, but problems like poor adaptability on irregular surfaces are still regulating the development of wheeled robots.

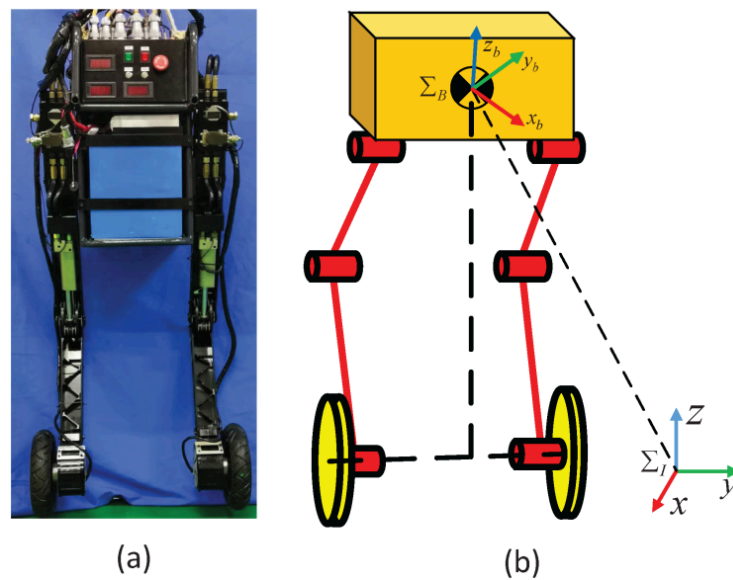


Figure 2. Imagery of wheeled robots [9]

2.1.2.2. Legged robots

By comparison, the advantages and disadvantages of legged robots are exactly opposite to those of wheeled robots. "Legged robots exhibit a strong terrain adaptability, compound motion mode, and autonomous passage ability in unknown and unstructured environments" [13]. For example, legged robots can move faster on sand, mud or mountain roads by using legs. Legged robots are adept to use their discrete footsteps to travel on both continuous and discontinuous surfaces and step or climb over obstacles in their path, which provides legged robots with versatile mobility particularly in uneven and challenging terrains. Also, "legged robots' agility and maneuverability also contributed to robots' stability, these qualities allowed legged robots to navigate accurately" [14]. What is more, legged robots need to maintain fixed contact with the ground. Reduced terrain deformation and reduced rolling friction between the robot and the ground makes legged locomotion advantages on soft surfaces, like sandy soil. The humanoid robot shown in Figure 3 is also a kind of legged robot, they often use human-like legs with alternating gait to generate movements, which is a key component of working. However, although their mobile efficiency is higher, the more complex structure of the robot resulted in a huge energy consumption. The legs of the legged robots support their body and provide most impetus, so when the legs are accidentally broken, it leads to severe problems and also hard to fix.

To summarize, legged robots are more suitable for locomotion on uneven terrains as they are able to use legs to cross over, providing considerable convenience for their movements. However, the energy requirement is significant, while when there are malfunctions, the repair cost is extremely high.

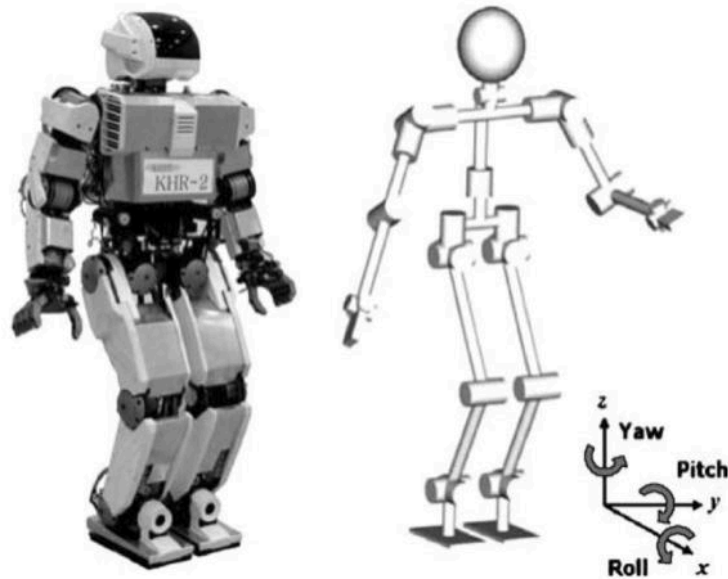


Figure 3. An imagery of legged robots [15]

2.1.2.3. Wheel legged robots

Due to the limitation of wheeled robots and legged robots, researchers integrated advantages of both types of robots and designed a wheel-legged hybrid mobile robot, which can achieve multi-modal movement, combining the speed advantages on flat terrains with the advantages to cross over obstacles on uneven terrains. This technology has been gradually applied in different scenarios such as disaster area rescue and good transportation. As for wheel-legged robots' structure, they have a relatively simple mechanical control system and lower energy consumption compared with legged robots. These robots are equipped with wheels in contact with the ground, similar to the driving structure of wheeled robots, and wheels are connected to the robot's base through leg linkages. The servos on the base controls the movement of the legs. As shown in Figure 4, this is a typical wheel-legged robot with actuating wheels and actuating legs. "Usually, the structure and degree of freedom distribution of this robot exhibit bilateral symmetry. This wheel-leg combination architecture has innovative and terrain-adaptive motion patterns, enabling the robot to efficiently perform tasks in structured and unstructured environments" [16].

To sum up, after integrating the efficiency of wheeled robots' mobility with the strong terrain adaptability of legged robots, wheel-legged robots have become one of the most important and innovative style of robot, widely used in different situations.

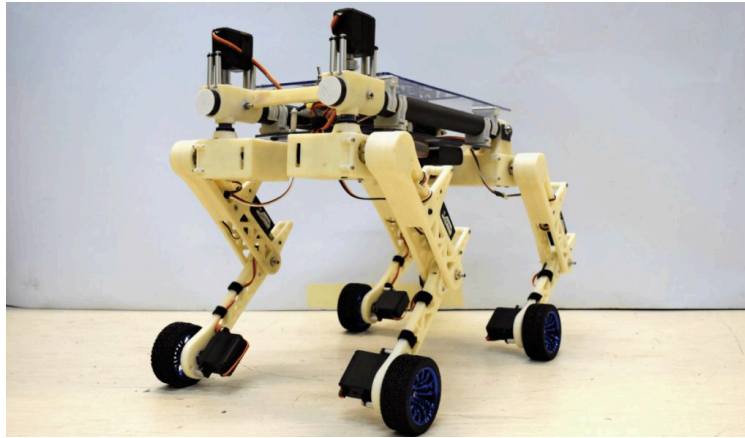


Figure 4. An imagery of wheel-legged robots [17]

2.2. Control methods

2.2.1. Model Predictive Control

Model Predictive Control (MPC) is a methodology for controlling bipedal robots which can fully utilize the performance of the hardware and are able to respond promptly to the constantly changing environment. During operation, MPC can quickly adjust the control parameters based on updated state feedback to adapt to different terrains without pausing. Consequently, bipedal robots can quickly respond to unexpected pushes or terrain variations. "Model predictive control also provides a structured approach for bipedal robots by continuously optimizing future foot placements and body trajectories under dynamic and terrain constraints to achieve stable, adaptive, and safe locomotion" [18]. Apart from that, MPC has a significant advantage on uneven terrains. It can estimate the ground contour information to let bipedal robots achieve a more stable walking on irregular environments. At the same time, MPC can also predict possible terrains in the future based on the current ground type which helps to generate more natural and coherent gait patterns. As for robots' various walking patterns, MPC can be applied to different gaits of bipedal robots as it integrates patterns like walking, running, turning or recovery behaviors into a single optimization formula. For these reasons, MPC was an excellent method to address specific challenges of controlling dynamic motions in bipedal robots.

In conclusion, the future-prediction mechanism of MPC and the unique parameters of MPC enable bipedal robot to be used in distinct terrains and helps bipedal robots to upgrade the adaptability of bipedal robots to uneven or flat terrains.

2.2.2. Hybrid Zero Dynamics

Hybrid Zero Dynamics (HZD) is currently a famous method for controlling robots, HZD was first introduced by E.R. Westervelt et al. [19] and it has become one of the most influential methods for achieving stable and dynamically consistent walking in different terrains, particularly rugged terrains. It is a control framework that a set of joint angle-related virtual constraints is set to ensure that the robot's movement occurs on a low-dimensional surface within the zero dynamics manifold. At the same time, this manifold remains unchanged during the continuous movement of the robot and during the discrete movement involving collisions with the ground, which helps bipedal robots achieve stable periodic walking gaits on different terrains. It also offers a systematic approach to designing the controller and ensures the achievement of a periodic, human-like walking pattern. "It is able to accommodate under actuation in bipedal robots and thereby move beyond quasi-static, flat-footed walking gaits" [20].

In general, Hybrid Zero Dynamics contributed to enhancing the adaptability of bipedal robots on rough and irregular terrains through confining their movements and maintaining consistent dynamic characteristics during continuous and collision phase.

2.2.3. Zero Moment Point

Zero Moment Point (ZMP) is a concept related to the dynamics and control of leg movements. It indicates a point where the reaction forces at the contact points of the robot's feet with the ground do not generate any torque in the horizontal direction. This concept is based on an assumption that the contact area is a plane and has sufficient friction to prevent the feet from slipping. "The walking style of the biped robot is being entirely centered on the idea of the Zero Moment point, which has been experimentally demonstrated and is widely recognized" [21]. ZMP is extremely suitable for slow or quasi-static walking on relatively flat terrain because it keeps the robot's center of mass within the support polygon, so it is easy to maintain stable foot placement. For tasks like which take place on flat terrains, ZMP was widely used. "ZMP also has relatively simple dynamic model requirements, which can reduce the computational burden" [22]. Furthermore, ZMP can plan the position of the feet and the center of gravity, so the possibility of robots flipping over is reduced.

After all, the superb advantages of ZMP benefits bipedal robots to work efficiently on flat terrains. Even though newer methods like HZD and MPC offered more flexibility, ZMP-based control remains relevant as it plays an important role in managing robots' walking patterns in structured environments.

2.3. The adaptability to different terrains

The technology for enhancing the adaptability of bipedal robots to different terrains is of vital importance for the development of the robotics field. It can be applied in rescue, transportation and other forms of work, and can bring significant benefits to humanity. At the same time, for bipedal robots to be applicable to various scenarios, they must be able to leave the laboratory and walk in complex real-world environments.

2.3.1. Cassie bipedal legged robot

Kumar et al. [6] tested their Cassie bipedal robot in three scenarios, nominal ground, slippery ground, and a rough terrain with different softness. Cassie robot was tested for its adaptability on nominal ground while carrying a 4-kilogram load as shown in Figure 5(a). The robot maintained a forward walking speed with no significant drift to other directions. During the slippery ground test as shown in Figure 5(b), they used a plastic sheet with water on the surface to cover the ground in between in order to reduce the ground friction coefficient, this imitates terrain surfaces after raining. They observed that when the robot steps onto the plastic sheet, there are significant slips between the robot feet and ground. Although unexpected contact changes lead to several uneven steps, the robot was able to successfully meet the requirements for traversing slippery surfaces. As for rough terrain experiments presented in Figure 5(c), they introduced challenging, irregular types of terrains and contacts in the tests. They use soft foam and wooden planks and place them on the ground to simulate changed terrains. When controlling the robot to walk across the region, the robot shows linear and stable footsteps on wooden planks but discrete footsteps on soft foam. The contact region is on the sole when robot steps on a rigid plank while the contact always happened on the robot foot if it steps into the soft foam, leading to the imbalance of robot.

In summary, Cassie robot is able to cross stably on rigid plank, slippery ground and on nominal ground while carrying a 4-kilogram load, which reveals such legged robots are able to move stably without losing balance in a relative smooth or slippery ground, a relative high level of adaptability can be concluded by the results of the experiments. However, the changes of softness and contact shape leads to a decrease in adaptability for Cassie robot.

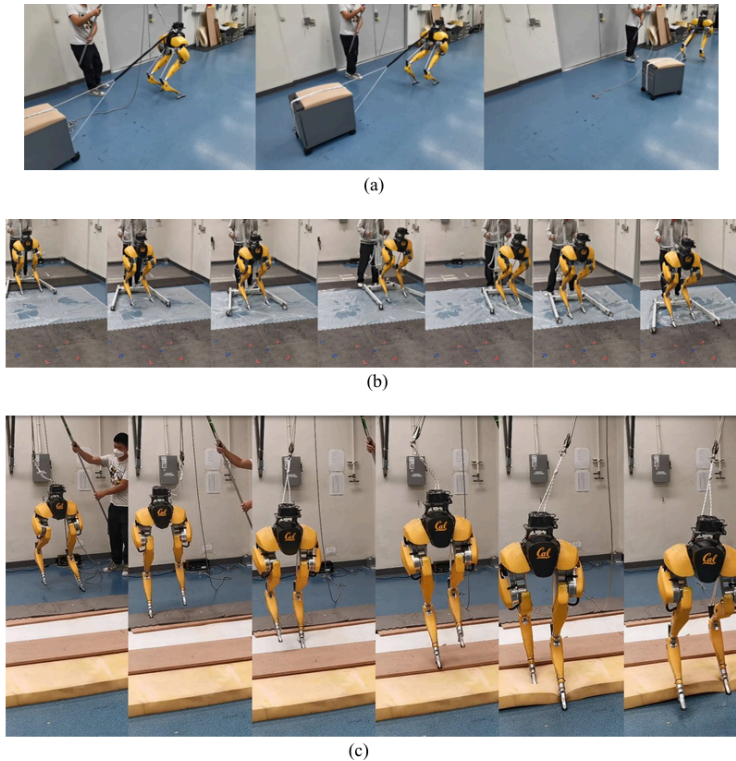


Figure 5. (a) Nominal ground (forward); (b) nominal ground (sideways); (c) towing a ~40 kg payload on wheels; (d) slippery ground; (e) uneven ground with variable softness [6]

2.3.2. Digit humanoid bipedal robot

As shown in Figure 6, Radosavovic et al. [23] used a digit humanoid robot, combined with their method: They proposed a learning-based approach for real-world humanoid robot locomotion with a controller. They tested robot Digit is a general-purpose humanoid robot developed by Agility Robotics. They conducted a series of experiments on different terrains in the laboratory. Each experiment instructed the robot to walk forward at a constant speed, and different items were laid on the ground respectively: rubber, fabric, cable, and bubble film, as shown in Figure 6. These items changed the roughness of the terrain. They discovered that their policy enabled reliable outdoor walking without falling down, and robust to external disturbances, could traverse different terrains, and carried payloads of varying mass. Furthermore, they surprisingly found their approach outperforms the most advanced model-based controllers. Although obstacles are limiting the adaptability and continuity of the bipedal robot, the robot with the controller was still able to travel stably on all these terrain types, thereby showing its strong adaptability when meeting obstacles or terrains with changed softness.

In conclusion, the digit robot showed superb adaptability on unstructured terrains with the use of the designed controller, digital robots can stably walk in some rough and steep terrains. However, the simulated terrain has a certain difference from the truly rough terrain, it must be more uneven and rough, with more frequent change in terrain height. This resulted in much more severe problems with the digital robot's adaptability, at the same time, the speed and efficiency of walking must be improved to ensure a more effective and safe action of the robot.

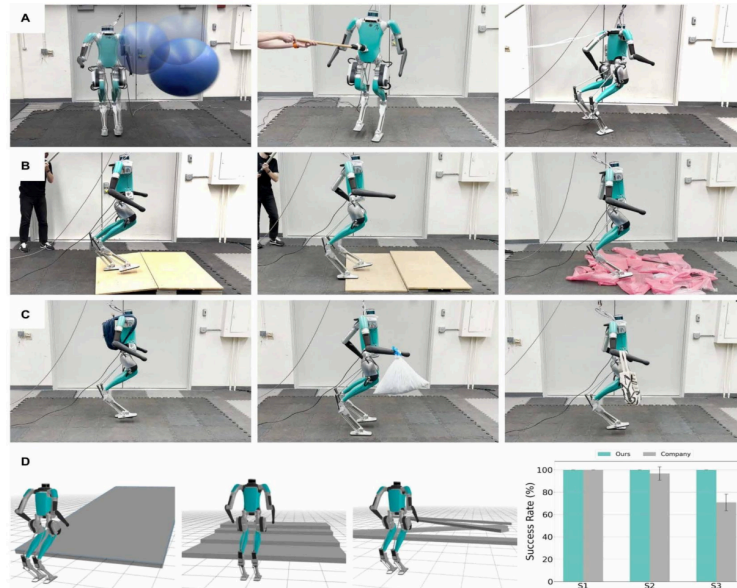


Figure 6. The results of digit robot on distinct terrains [23]

2.3.3. SLIDER bipedal robot

It is suggested that the adaptability of bipedal robot also varies when in uneven terrains with different flatness and height. Wang et al. tested a SLIDER bipedal robot which is a knee-less bipedal robot designed by the Robot Intelligence Lab at Imperial College London [24]. They invented a reactive controller that enables robots to blindly walk over uneven terrains. This controller is used to address the inconsistency between simple models used in high-level planning and the complete dynamics of robots. With the help of a full body controller, the robot's feet exhibit strong flexibility, which helps the robot transition between different terrains without any terrain information.

Pictures in the first row in Figure 7 represent different terrains at which the robot is tested while pictures in the second-row plots desired and measured CoM position in corresponding scenarios. As shown in Figure 7 A, B, C, they first tested their robot on smooth uneven terrain, a slope with 15° and a wave field with three different angles: 15, 10, 5. During the test, SILDER robots demonstrate different moods with distinct adaptability. For the first test with slopes and wave fields, the robot moves continuously with a speed of 0.3 meters per second, which shows great adaptability on those uneven but smooth terrains. Then, SLIDER is tested on discrete uneven terrain. In this test, there is a contrary result. In their experiment, they used different stairs with various heights to imitate the differentiation of height or flatness in nature. The highest step the robot can walk over is 30 cm, for higher steps the foot of the robot would hit the edge of the stairs and get stuck. Here, robots are not able to cross terrains with significant height differences. The discrete uneven terrain provides bigger instantaneous variations to terrain height than the smooth uneven terrain. As shown in Figure 7 D, the robot can walk blindly over a set of stairs with a forward velocity of 0.6 m/s.

In general, the SILDER robot are more stable with strong adaptability when walking on slopes, or smooth terrains, however, when meeting discrete uneven terrains, the instantaneous height of the terrain causes severe problems for both the adaptability and the stability of the bipedal robot.

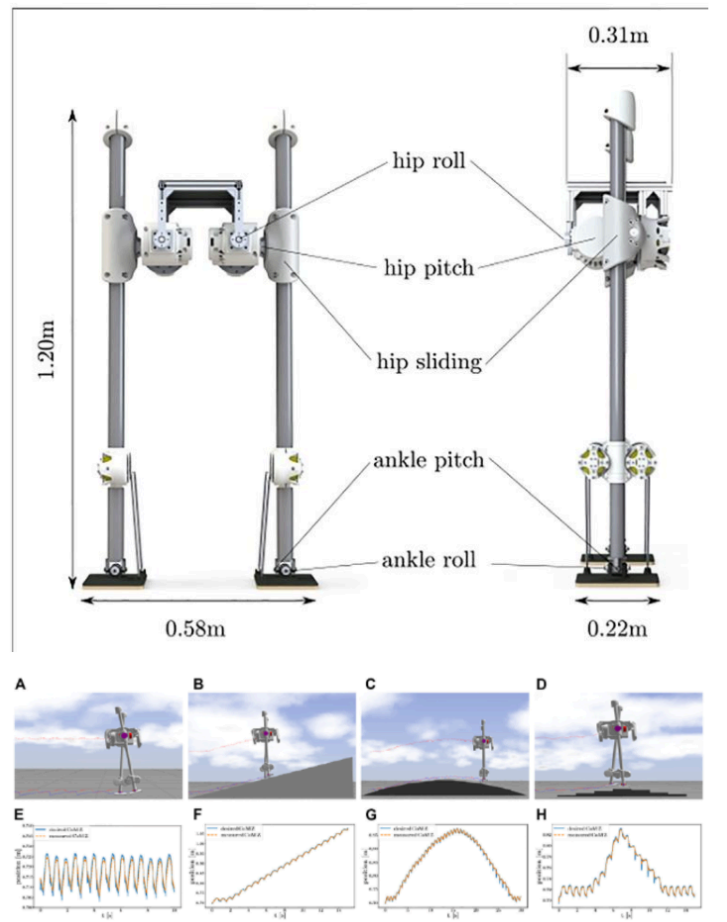


Figure 7. Dimension and joint configuration of the SLIDER robot [24]

2.3.4. Other robots

More results are also done by other researchers such as Wu, J et al. [7], who proposed an automatic synthesis bipedal control framework that can modify the end effector trajectory during runtime to adapt to uneven terrain; Gong, Y et al. tested Cassie robot and find it is able to walk and stand on sidewalks, grass, snow, sand, and burning shrubs, demonstrating her practical ability and robustness in various real-world terrains and disturbances [25]; Li and Nguyen proposed that adaptive frequency MPC combined with kinematic dynamics optimization and Whole-Body Control (WBC) for discontinuous "stepping stone" terrain [26]. Most of the bipedal robots showed strong adaptability when meeting uneven terrains, whether combing the robots with controllers or unique designed structure.

In general, after researchers carrying out different experiments with distinct bipedal robots moving in various man-made or natural terrains, it can be seen that bipedal robots are able to overcome their speed, efficiency, and the ability to adapt frequent change in terrain height and species, and maintain a high level of adaptability whether on slippery ground, unstructured ground or structured ground though the change of softness might negatively impact it's stability. Next, the discussion part will show some popular questions and further show the advancement of bipedal robots' adaptability.

3. Discussion

3.1. Bipedal robots are able to adapt to more and different terrains

Nowadays, improvements like new controllers, new controlling methods are carried out by researchers and firms, bipedal robots' adaptability to different terrains had been greatly strengthened, as they are able to adapt more kinds of terrains perfectly.

This can be proved by various evidence.

Kumar et al. [6] has tested their Cassie robot on slippery, tough and nominal grounds. They imitate natural uneven terrains by adding soft foam and wooden planks, when the robot was walking through them, they change their contact type by using different parts on robots' legs to better adjust their walking patterns. For example, they use their sole to contact with rigid plank but use their foot for soft foam. Although the softness of the terrains the robot was walking on changes significantly, the robot still reveals strong adaptability to walk on those terrains, as they can maintain forward walking speed with no significant drift to other directions. In another experiment, they tested their bipedal robot on uneven terrains, the robot maintained stable and consistent moving steps. After these series of experiments, it can be concluded that the Cassie bipedal robots they use are able to walk on lots of undetermined softness and uneven terrains.

Zhong et al. generated experiments on NAO robots which took stair-climbing as the core scenario [27]. Stairs represent uneven terrain in which ascending movements correspond to convex terrain and descending movements correspond to concave terrain. Stairs involved an obvious convex-concave change, and robots need to perform high-dimensional nonlinear control involving over ten degrees of freedom. After testing several times, the robot showed brilliant adaptability to uneven terrain under different controlling methods. It can maintain the smoothness of joint trajectories, such as dynamically adjusting the ankle joint pitch angle according to walking distance to adapt to terrain. The robot's sole FSR sensors are able to feed background pressure, dynamically adjusting plantar pressure distribution and center of gravity offset. It adapted to terrain convexity and concavity through roll and pitch motions of leg joints, with joint angles changing appropriately with walking distance. These experiments confirm that the humanoid robot can adapt to a large amount of different uneven terrain with uncertain convex-concave features.

Radosavovic et al. used a digit humanoid bipedal robot to generate real-world and simulated experiments [23]. Their results showed that the humanoid robot enables the robot to walk consistently without falling down, and robust to external disturbances, the robot are capable to traverse different terrains and carried payloads of varying mass. They also use different materials with different softness to demonstrate the adaptability of their robots by letting the robot walk through them. The robots are still able to cross it easily with no accident happening. These experiments carried out by scientists showed same conclusion, which more robots with different types are able to walk on more kinds of terrains.

However, some people will argue that bipedal robots are not able to cross terrains with height differences, as they may lose their walking patterns, posture or even lose their walking ability. Based on this hypothesis, scientists have proved lots of bipedal robots still maintain stable waking gaits when walking on terrains with height differences, which contradicts the hypothesis. Wang et al. tested a biped robot called SLIDER which is a knee-less bipedal robot [24]. Different slopes were used in their experiment to imitate the height difference on a terrain. After the experiment, the robot moves stably with a speed of 0.3meters per second, showing that the robot had great adaptability on those slopes. We can see that the SLIDER robot is able to adapt to terrains with various gradients. What's more, similar results were also seen in the experiment of Radosavovic et al. [23]. Their previous experiment suggested that their digit robot can carry varying mass and move on terrains with different softness, now, they tested their robot also on slopes but with distinct gradient. They were

running their robot from the bottom of the slope to the top with a maximum gradient of 8.7%. Surprisingly, the robot not only moves continuously, but it also even walked quickly across the slope.

At the same time, Nishiwaki et al. tested their HRP-2 humanoid bipedal robot on unknown terrains with height differences such as rigid platforms and step-like surfaces [28]. The HRP-2 humanoid robot maintained stable footsteps and can continuously walk on those terrains. Nishiwaki used terrains with known accurate dimensions to simulate real-world height difference scenarios. For the experiment result, all experiments demonstrate the robot is able to successfully navigate height differences with the largest height measurement error at 11.4 millimeters, within the control system's acceptable range. Consequently, the HRP-2 humanoid robot can adapt to unknown terrains with different height differences through integrated laser perception adaptive footstep planning and robust walking control.

Joe and Oh used DRC-HUBO+ humanoid robots to test its' adaptability on obstacle terrains [29]. They put their robots on sloped surface including stony areas and lawns. The terrain height and slope were up to 8 degrees, but the robot walked with fluent footsteps, and unchanged walking patterns. This confirmed that the robots can successfully adapt to those terrains even on stony areas with 2 to 4 cm high stones. After all, DRC-HUBO+ humanoid robot adapts well to unknown terrains with different height differences and slopes. It can not only achieve stable terrain-blind walking through slopes with various degrees, but also on stones which had a relative larger height difference.

After applying those three examples, SLIDER robot, DRC-HUBO+ robot and HRP-2 robot all demonstrated great adaptability on terrains with height difference, whether on slopes, stone grounds or other forms of terrains. Similarly, modern bipedal robots now demonstrate meaningful adaptability across a range of uneven and changing terrains, though performance still varies by terrain type and control method. Modern bipedal robots now demonstrate meaningful adaptability across a range of uneven and changing terrains

3.2. Robot advancement of gait control increases its adaptability to terrains

Currently, when more and more researchers take part in improving the adaptability of bipedal robots, not only the shape of bipedal robots changed, but also more advanced or improved gait controlling methods are invented or tested. So the advancement of gait control methods will increase the adaptability of bipedal robots.

In Vukobratović and Borovac research among Zero-Moment point (ZMP) gait control, they discovered that when robots are moving on uneven, inclined or irregular surfaces, the robot can maintain dynamic balance and will not experience significant tilting or directional deviation by the use of ZMP gait control [30]. The control system will keep the supporting points within the zero-point support area in the robot's support area, ensuring stable weight distribution. The ZMP gait control method is benefit for enhancing the robot's adaptability on uneven terrains. The robot can adjust its contact type and walking mode according to the real-time terrain conditions, which maintains a stable and consistent pace.

Similar results are seen in research done by Martin and Gregg [31]. They improved the bipedal model based on HZD to possess human-like gait variation characteristics which enhances its adaptability in uneven terrains. In their results, even when robots are crossing across irregular surfaces that cause irregular joint movements and stride variations, the robot can still be able to maintain stable movement, continuously advance forward, and avoid significant imbalance. Which is to say, the improvement of the control method based on HZD significantly enhances the adaptability of the bipedal robot to uneven terrains. The robot can cope with unpredictable stride variations and disturbances caused by the terrain, maintain a human-like gait, and avoid falling, increasingly demonstrating its reliability in real-world, irregular environments.

Moreover, Scianca et al. validated their Intrinsically Stable Model Predictive Control (IS-MPC) framework on humanoid robots NAO and HRP-4 [32]. From their experiment, these robots can maintain stable movement

on uneven experimental surfaces without any imbalance. Therefore, in the simulation and actual experiments conducted on small and large humanoid robots, the gait control method based on IS-MPC has enhanced the robots' adaptability to uneven terrains. The robots can adjust using preview information, maintain stable balance through the control method of zero moment points and kinematic constraints, and avoid falling by optimizing the gait parameters in real time.

However, some people discussed that only traditional and popular gait controlling methods such as MPC can increase robots' adaptability. According to this question, there are still many other newly invented ways which lead to the same result as the traditional method. Mihalec et al. conducted tests on their bipedal robot model on a low-friction and slippery terrain, where the risk of foot slips is likely to occur [33]. They achieved real-time recovery of the robot's adaptability on the ground by focusing on sliding recovery. The experimental results showed that the robot could improve its adaptability on slippery and uneven terrains by evaluating its movement state in real time and applying appropriate control strategies according to different risk levels.

Liu et al. conducted tests on an anthropomorphic robot based on Hubo+ on uneven terrain with protrusions and shallow depressions [34]. The control system uses a 3D dual SLIP model as a "template" to generate human-like center of gravity trajectories and foot positions. This model captures the soft and spring-like characteristics of the legs, enabling the robot to absorb shocks from uneven terrain. The gait control method based on the three-dimensional dual sliding inertia principle allows the robot to utilize the compliant leg dynamics to absorb terrain shocks, adapt to height changes through real-time trajectory adjustment, and maintain stability through disturbance correction, thereby upgraded the robot's ability to adapt to uneven terrain.

Astudillo et al. conducted tests on a 10-degree-of-freedom bipedal robot on uneven terrains [35]. The experiment combines the Zero-Moment Point (ZMP) principle with a new Linear Inverted Pendulum Model (LIPM) to enhance terrain adaptability. When the robot encounters unexpected protrusions or slight depressions, this controller will quickly adjust the joint angles to restore the predetermined gait. The robot's center of gravity remains within the support polygon during both single-support and double-support phases, thus preventing falls caused by uneven terrain. This gait control method utilizes biomechanical movements similar to those of humans to adapt to terrain changes. At the same time, it maintains core stability based on the zero-moment point principle and handles small disturbances through real-time trajectory correction, enhancing the robot's adaptability to variable terrains.

In general, it can be concluded that both traditional and new controlling methods contributed to the improvement of bipedal robots' adaptability, as there are even more than three kinds of new and traditional methods. New methods can rely on their ability to increase footstep adaptability or imitating human locomotion to increase overall stability when meeting distinct terrains. These new and traditional controlling methods both benefit for the adaptability of bipedal robots.

3.3. The compliant structure of bipedal robots increases its adaptability

Compliant structures are commonly used in bipedal robots as it contributes to increase the adaptability of bipedal robot, it can help the robot to absorb landing impacts and maintain a continuous and stable walking pattern.

Reher et al. tested a Cassie bipedal robot on various uneven terrains, including indoor floors, outdoor grounds and rough surfaces [36]. This robot imitates the spring compliant structure of natural legs, enabling it to better adapt to the unevenness of the terrain. When encountering unexpected rough sections, the springs will deform to maintain contact with the ground, allowing the robot to maintain a stable gait and stable center of gravity movement on uneven ground. This robot's compliant structure, effectively used passive flexibility to

absorb impacts, adapts to height differences through natural deformation, and works in coordination with active control to correct disturbances. Consequently, the compliant structure enhances the stability of the robot's movement.

Singh et al. investigated a humanoid robot walking on compliant and uneven terrain [37]. During the experiment, when the foot of the robot encounters soft or uneven areas, the compliant structure allows the leg to compress slightly. This soft interaction reduces sudden force peaks, which not only gives the controller more time to react and prevent destabilizing shocks, but also helps the robot to absorb the terrain impacts. After the experiment, they concluded that the robot achieves steadier contact, improved shock tolerance, and greater robustness when walking across unpredictable or deformable terrain.

Iida et al. experimented with a bipedal robot with compliant legs on uneven terrains [38]. The compliant structure of this robot mimicked the flexible structure of human legs' muscle-tendon system, it can achieve the effect of enhancing stability. The robot can utilize the passive elasticity of the flexible structure to absorb terrain impacts, adapt to height differences through organic deformation, and achieve self-stabilization with minimal control. This flexible design dramatically helps the robot to achieve a more stable adaptability on irregular terrains through intrinsic dynamic interaction.

However, some people suggest that the compliant structures of bipedal robot will reduce energy efficiency, as they walk on soft or uneven terrains. Zhou et al. conducted tests on the compliant humanoid robot COMAN [39]. The compliant structure on the robot stores elastic energy when the elastic component is in contact with the ground and releases it when pushing off. This is beneficial for recovering mechanical energy to reduce the energy input to the motor, saving energy usage and improving energy efficiency. The active coordinated control of the robot can optimize the stiffness and damping of the joints in real time, making the gait transition smoother and contributing to energy conservation. Therefore, the compliant structure of this robot combined both physical elasticity and active adjustment of stiffness, which benefits improving energy efficiency by mimicking the energy-saving mechanism of living organisms.

Moreover, Kim used a bipedal robot with biomimetic compliant feet to carry out experiments [40]. The robots are equipped with springs to imitate the ligaments of human feet, which brought advantages in optimizing joint operation and reducing energy waste. In his experiments, the elastic springs absorb the ground impact force when the feet touch the ground. The peak torque of the knees and hip joints and decreasing the energy required to resist rigid collisions. At the same time, the compliant structure can reduce the cumulative workload of the joints over time and minimize unnecessary energy consumption. Compliant foot avoided the waste of energy due to stiff movements, and optimizes the transfer of mechanical energy during walking, and consequently improved energy utilization efficiency.

Vanderborght et al. conducted tests on the bipedal robot Lucy which is powered by pleated pneumatic artificial muscles with adjustable compliance [41]. The compliant structure of this robot has controllable stiffness. The robots are able to leverage natural mechanical principles and optimize the performance of the actuators, which the energy efficiency has been significantly enhanced. More specifically, the compliant structure of the robot allows for adjusting its stiffness to match the natural stiffness required for the desired trajectory it reduced the energy needed to counteract deviations from natural movement and minimizing air consumption. At the optimal stiffness, the natural pressure of the actuators is highly consistent with the required pressure, avoiding frequent pressurization and depressurization, and thus avoided energy waste.

In conclusion, the compliant structure of bipedal robots significantly increased its adaptability to various terrains as it can help to increase energy efficiency by mimicking human legs; Also, it is able to absorb terrain impact by adjusting the stiffness of the leg, which generally shows the contribution of compliant structure to bipedal robots' adaptability.

4. Conclusion

This study focuses on the core research question: "To what extent can bipedal robots adapt to complex environments?" The essay aims to explore the adaptability of bipedal robots when meeting different terrains based on their influencing factors, existing challenges, and improvement paths of terrain adaptability. The essay seeks to clarify robots' mechanism and control logic behind robots' adaptive performance, and also evaluate bipedal robots' practical application potential. For the research technique, by adopting comprehensive experiments made by previous or recent researchers which tests the adaptability of bipedal robots, this essay introduced the types, mechanism, controlling method of bipedal robots while selecting numerous popular and authoritative researches and find popular discussions about the factors which influenced robots' adaptability, to discuss the extent of the adaptability of bipedal robots to different terrains. It covers typical bipedal robots such as Cassie, Digit, and SLIDER, and analyzes three mainstream control methods: MPC, HZD, ZMP as well as the role of compliant structures. The overall results indicate that bipedal robots can greatly adapt to various kinds of terrains which they have achieved significant progress in adapting to complex environments and current bipedal. Legged and wheel-legged robots which were supported by advanced control algorithms and compliant structures can stably traverse various terrains including flat ground, slippery surfaces and slopes. They can adjust gait patterns, contact modes, and center-of-mass trajectories in real time to cope with changes in terrain softness. Specifically, MPC and HZD excel in dynamic and rugged terrain adaptation, while compliant structures enhanced shock absorption and energy efficiency. However, robots are sometimes still struggled with large discrete height differences, as they often lost their balance when meeting a dramatic change in terrain height or meeting unpredictable change in terrain softness and type. The research contributes practically by confirming that bipedal robots are ready for real-world deployment in works such as post-disaster rescue and exploration work, which provided a theoretical and empirical basis for their industrial application. It shows how the current situation and level of ability for robots to adapt to various terrains. However, the work currently exists some drawbacks. The limited parameter and bipedal type are the main parts. Due to the lack of bipedal robot type, only some popular, significant bipedal robots were taken into account, but some uniquely-designed robots are not listed, this means that some unpopular bipedal robots may still face unsolved problem when meeting uneven terrains. Also, the parameter of the methods are also a problem. Due to the limitation of bipedal robot type, only a few amount of parameters are carried out in the essay to show robots' mechanism and adaptability. To address existing limitations, future research should focus on exploring more kinds of bipedal robots which differ from popular robot structures. Also, more kinds of controlling method and controversial argument should be considered, which helps to provide more parameters of bipedal robots. Through generating these two works, it can help to lay a more reliable and persuasive essay to show different bipedal robots' adaptability to different terrains.

References

- [1] Raibert, M. (1986). *Legged robots that balance*. MIT Press.
- [2] Furusho, J., Akihito, S., Masamichi, S., & Eichi, K. (1995). Realization of bounce gait in a quadruped robot with articular-joint-type legs. In *Proceedings of the IEEE International Conference on Robotics and Automation* (pp. 697–702). IEEE.
- [3] Kato, I., & Tsuiki, H. (1972). The hydraulically powered biped walking machine with a high carrying capacity. In *Fourth Symposium on External Extremities*. Yugoslav Committee for Electronics and Automation.
- [4] Rus, D. (2015). *How technology breakthroughs will transform everyday life*. https://scholar.google.com/citations?hl=en& user=910z20QAAAAJ& view_op=list_works& sortBy=title

- [5] Khan, M. S., & Mandava, R. K. (2023). A review on gait generation of the biped robot on various terrains. *Robotica*, 41(6), 1888–1930. <https://doi.org/10.1017/S0263574723000097>
- [6] Kumar, A., Li, Z., Zeng, J., Pathak, D., Sreenath, K., & Malik, J. (2022). Adapting rapid motor adaptation for bipedal robots. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 1161–1168). IEEE. <https://doi.org/10.1109/IROS47612.2022.9981091>
- [7] Wu, J., & Popović, Z. (2010). Terrain-adaptive bipedal locomotion control. *ACM Transactions on Graphics*, 29(4), Article 72. <https://doi.org/10.1145/1778765.1778809>
- [8] Ngamkajornwiwat, P., Homchanthanakul, J., Teerakittikul, P., & Manoonpong, P. (2020). Bio-inspired adaptive locomotion control system for online adaptation of a walking robot on complex terrains. *IEEE Access*, 8, 91587–91602. <https://doi.org/10.1109/ACCESS.2020.2992794>
- [9] Cui, Z., Xin, Y., Liu, S., Rong, X., & Li, Y. (2022). Modeling and control of a wheeled biped robot. *Micromachines*, 13(5), Article 747. <https://doi.org/10.3390/mi13050747>
- [10] Ficht, G., & Behnke, S. (2021). Bipedal humanoid hardware design: A technology review. *Current Robotics Reports*, 2, 201–210. <https://doi.org/10.1007/s43154-021-00050-9>
- [11] Ficht, G., Allgeuer, P., Farazi, H., & Behnke, S. (2017). NimbRo-OP2: Grown-up 3D printed open humanoid platform for research. In *2017 IEEE-RAS 17th International Conference on Humanoid Robotics (Humanoids)* (pp. 669–675). IEEE. <https://doi.org/10.1109/HUMANOIDS.2017.8246949>
- [12] Ficht, G., Farazi, H., Brandenburger, A., Rodriguez, D., Pavlichenko, D., Allgeuer, P., & Behnke, S. (2018). NimbRo-OP2X: Adult-sized open-source 3D printed humanoid robot. In *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)* (pp. 1–9). IEEE. <https://doi.org/10.1109/HUMANOIDS.2018.8625012>
- [13] Bellicoso, C. D., Jenelten, F., Fankhauser, P., Gehring, C., Hwangbo, J., & Hutter, M. (2017). Dynamic locomotion and whole-body control for quadrupedal robots. In *Proceedings of the 2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 3359–3365). IEEE. <https://ieeexplore.ieee.org/document/8206174>
- [14] Dan, A., Saha, S. K., & Krishna, K. R. (2024). A review on the stability of biped robots. *Journal of the Indian Institute of Science*, 104, 579–609. <https://doi.org/10.1007/s41745-024-00454-4>
- [15] Park, I. W., Kim, J. Y., Lee, J., & Oh, J. H. (2007). Mechanical design of the humanoid robot platform, HUBO. *Advanced Robotics*, 21(11), 1305–1322. <https://doi.org/10.1163/156855307781503683>
- [16] Guo, F., Wang, S., & Wang, J. (2022). Development status and key technology analysis for motion planning of wheel-legged hybrid mobile robot. *Control and Decision*, 37(6), 1433–1444. <https://doi.org/10.13195/j.kzyjc.2021.0052>
- [17] Liu, T., Zhang, C., Wang, J., Song, S., & Meng, M. Q.-H. (2022). Towards terrain adaptability: In situ transformation of wheel-biped robots. *IEEE Robotics and Automation Letters*, 7(2), 3819–3826. <https://doi.org/10.1109/LRA.2022.3148486>
- [18] Xu, Z., Xie, J., & Hashimoto, K. (2025). Human-inspired gait and jumping motion generation for bipedal robots using model predictive control. *Biomimetics*, 10(1), Article 17. <https://doi.org/10.3390/biomimetics10010017>
- [19] Westervelt, E. R., Grizzle, J. W., & Koditschek, D. E. (2003). Hybrid zero dynamics of planar biped walkers. *IEEE Transactions on Automatic Control*, 48(1), 42–56. <https://doi.org/10.1109/TAC.2002.806653>
- [20] Ames, A. D., Galloway, K., Sreenath, K., & Grizzle, J. W. (2014). Rapidly exponentially stabilizing control Lyapunov functions and hybrid zero dynamics. *IEEE Transactions on Automatic Control*, 59(4), 876–891. <https://doi.org/10.1109/TAC.2014.2299335>
- [21] Haldar, A. I., & Pagar, N. D. (2023). Predictive control of zero moment point (ZMP) for terrain robot kinematics. *Materials Today: Proceedings*, 80, 122–127. <https://doi.org/10.1016/j.matpr.2023.01.045>
- [22] Al-Tameemi, I., & Amanuel, O. (2025). Bipedal robots: A systematic review of dynamical models, balance control strategies, and locomotion methods. *Journal of Robotics and Control*, 6(3), 1240–1254. <https://doi.org/10.1016/j.matpr.2023.01.045>

- //doi.org/10.18196/jrc.v6i3.25595
- [23] Radosavovic, I., Zhang, T., Shi, B., Huang, J., Sreenath, K., & Malik, J. (2024). Real-world humanoid locomotion with reinforcement learning. *Science Robotics*, 9(90), Article eadi9579. <https://doi.org/10.1126/scirobotics.adi9579>
- [24] Wang, K., Fei, H., & Kormushev, P. (2022). Fast online optimization for terrain-blind bipedal robot walking with a decoupled actuated SLIP model. *Frontiers in Robotics and AI*, 9, Article 812258. <https://doi.org/10.3389/frobt.2022.812258>
- [25] Gong, Y., Hartley, R., Da, X., Hereid, A., Harib, O., Sreenath, K., & Grizzle, J. W. (2019). Feedback control of a Cassie bipedal robot: Walking, standing, and riding a Segway. In *2019 American Control Conference (ACC)* (pp. 4559–4566). IEEE. <https://doi.org/10.23919/ACC.2019.8814833>
- [26] Li, J., & Nguyen, Q. (2023). Dynamic walking of bipedal robots on uneven stepping stones via adaptive-frequency MPC. *IEEE Control Systems Letters*, 7, 1279–1284. <https://doi.org/10.1109/LCSYS.2023.3234769>
- [27] Zhong, Q., & Chen, F. (2016). Trajectory planning for biped robot walking on uneven terrain—Taking stepping as an example. *CAAI Transactions on Intelligence Technology*, 1(3), 197–209. <https://doi.org/10.1016/j.trit.2016.12.001>
- [28] Nishiwaki, K., Chestnutt, J., & Kagami, S. (2012). Autonomous navigation of a humanoid robot over unknown rough terrain using a laser range sensor. *The International Journal of Robotics Research*, 31(11), 1251–1262. <https://doi.org/10.1177/0278364912455720>
- [29] Joe, H.-M., & Oh, J.-H. (2019). A robust balance-control framework for the terrain-blind bipedal walking of a humanoid robot on unknown and uneven terrain. *Sensors*, 19(19), Article 4194. <https://doi.org/10.3390/s19194194>
- [30] Vukobratović, M., & Borovac, B. (2004). Zero-moment point – Thirty five years of its life. *International Journal of Humanoid Robotics*, 1(1), 157–173. <https://doi.org/10.1142/S0219843604000083>
- [31] Martin, A. E., & Gregg, R. D. (2016). Incorporating human-like walking variability in an HZD-based bipedal model. *IEEE Transactions on Robotics*, 32(4), 943–948. <https://doi.org/10.1109/TRO.2016.2572686>
- [32] Scianca, N., De Simone, D., Lanari, L., & Oriolo, G. (2020). MPC for humanoid gait generation: Stability and feasibility. *IEEE Transactions on Robotics*, 36(4), 1171–1188. <https://doi.org/10.1109/TRO.2020.2981674>
- [33] Mihalec, M., Zhao, Y., & Yi, J. (2020). Recoverability estimation and control for an inverted pendulum walker model under foot slip. In *2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)* (pp. 771–776). IEEE. <https://doi.org/10.1109/AIM43001.2020.9159028>
- [34] Liu, Y., Wensing, P. M., Orin, D. E., & Zhang, Y. (2015). Dynamic walking in a humanoid robot based on a 3D actuated Dual-SLIP model. In *2015 IEEE International Conference on Robotics and Automation (ICRA)* (pp. 5710–5717). IEEE. <https://doi.org/10.1109/ICRA.2015.7139995>
- [35] Astudillo, D., Minchala, L. I., Astudillo-Salinas, F., & Vázquez, F. (2018). A simple mapping methodology of gait biomechanics for walking control of a biped robot. In *2018 IEEE XXV International Conference on Electronics, Electrical Engineering and Computing (INTERCON)* (pp. 1–4). IEEE. <https://doi.org/10.1109/INTERCON.2018.8526387>
- [36] Reher, J., Ma, W. L., & Ames, A. D. (2019). Dynamic walking with compliance on a Cassie bipedal robot. In *2019 18th European Control Conference (ECC)* (pp. 2589–2595). IEEE. <https://doi.org/10.23919/ECC.2019.8795869>
- [37] Singh, R. P., Morisawa, M., Benallegue, M., & Kanehiro, F. (2024). Robust humanoid walking on compliant and uneven terrain with deep reinforcement learning. In *2024 IEEE-RAS 23rd International Conference on Humanoid Robots (Humanoids)* (pp. 497–504). IEEE. <https://doi.org/10.1109/Humanoids58906.2024.10769894>
- [38] Iida, F., Minekawa, Y., Rummel, J., & Seyfarth, A. (2009). Toward a human-like biped robot with compliant legs. *Robotics and Autonomous Systems*, 57(2), 139–144. <https://doi.org/10.1016/j.robot.2008.10.005>

- [39] Zhou, C., Li, Z., Wang, X., & Wang, Y. (2016). Stabilization of bipedal walking based on compliance control. *Autonomous Robots*, 40(6), 1041–1057. <https://doi.org/10.1007/s10514-015-9519-2>
- [40] Kim, B. H. (2013). Work analysis of compliant leg mechanisms for bipedal walking robots. *International Journal of Advanced Robotic Systems*, 10(9), Article 334. <https://doi.org/10.5772/56767>
- [41] Vanderborght, B., Verrelst, B., Van Ham, R., Van Damme, M., Beyl, P., & Lefeber, D. (2008). Development of a compliance controller to reduce energy consumption for bipedal robots. *Autonomous Robots*, 24(4), 419–434. <https://doi.org/10.1007/s10514-008-9084-z>