**A Comprehensive Review of Biped Robots Development, Key Technologies, Applications and Future Trends**

**Abstract:** As highly complex intelligent systems, bipedal robots integrate cutting-edge technologies from multiple fields such as mechanics, control, sensing, and artificial intelligence, demonstrating broad application potential. This paper systematically reviews the development history of bipedal robots, from the early theoretical foundations to the current breakthroughs in high-performance prototypes, with a focus on analyzing the progress of key technologies such as mechanical structure design, dynamic motion control, environmental perception, and human-robot interaction. Research shows that bipedal robots have achieved initial applications in multiple fields including industrial collaboration, social services, and disaster rescue, demonstrating good environmental adaptability and task execution capabilities. However, they still face significant challenges in dynamic balance control, energy autonomy, and human-robot collaborative safety. In the future, bipedal robots will continue to develop towards high dynamic performance, intelligent decision-making, and multi-scenario integrated applications. This paper aims to provide systematic technical references and application prospects for researchers in related fields.

**Key words:** biped robot; key technology; application field; Development trend

**1. Introduction**

Under the background of the rapid development of science and technology, robotics has increasingly become a key force to promote changes in various industries. As a typical representative of humanoid robot, biped robot has unique advantages in many complex scenes because of its unique biped walking mode and human-like form, which attracts the attention and investment of many scientific research teams and enterprises around the world [12, 13]. A comprehensive and in-depth study of biped robots will not only help to sort out its development context, but also clarify the key technology progress and challenges at this stage, and provide strong support for subsequent scientific research innovation and application promotion. In this paper, the development process, key technologies, application fields, challenges and development trends of biped robots will be systematically described.

**2. Development history of biped robot**

**(1) Early stage of theoretical exploration**

As early as the middle of the 20th century, scientists began to be interested in the motion principle of biped robots and carried out theoretical exploration. Limited by the technical level at that time, researchers mostly used simple mechanical linkages to simulate the basic movement of human legs, and tried to understand the mechanism of bipedal walking by establishing basic kinematic models [14]. For example, some early theoretical models tried to use multiple links to form a simple "leg" structure and analyze its motion posture at different joint angles [15]. Although these models are rough and have a big gap with the actual applicable robots, they have laid an important theoretical foundation for the subsequent development of biped robots.

**(2) Preliminary prototype development stage**

From the 1980s to the end of the 20th century, with the gradual development of mechanical manufacturing, electronic technology and other fields, the development of biped robots has entered the prototype stage. During this period, a number of iconic biped robot prototypes appeared [16, 17].

The research of biped robot first appeared in Japan. Professor Kato Ichiro of Waseda University [1] began to study biped robot technology in 1960. In 1972, Waseda University launched the highly influential intelligent robot WABOT-1 [2], which is about 2 meters high and weighs 160 kilograms. It also has human-like vision system, limb control system and dialogue system. It has 26 degrees of freedom, almost all the characteristics of humanoid robots, and the robot can also complete simple walking functions. As shown in fig. 1. In 1984, the second generation of intelligent robot WABOT-2 robot was successfully launched. The robot has 50 degrees of freedom [3]. The robot is defined as a "professional robot" because it can play the piano through its own vision and finger control. In 1981, Waseda University introduced the WAL-9DR robot, which is about 0.5 meters high, weighs about 40 kilograms, and has 10 degrees of freedom. The robot successfully completed static gait walking for the first time.



Fig. 1 Biped robot developed by Waseda University



（1）P2 （2）P3

Figure 2 Honda P Series

In addition to universities and research institutes in Japan, many scientific and technological enterprises have also carried out research on biped robots. Japan Honda started the research of its robot series in 1993 [4-6] and launched the P series biped robot (as shown in Figure 2). The P series robot uses human beings as the design template and has a similar appearance to human beings. The P2 robot is about 180cm tall and weighs about 120kg. The robot also has built-in power supply and system hardware. It can break away from the cable to achieve more stable dynamic walking of both feet, as well as difficult movements such as climbing steps. In 1997, Honda introduced a new generation of P3 robot on the basis of P2. The robot is equipped with a large number of sensors, which can determine the surrounding environment through sensors and achieve stable walking on slopes. The appearance of these early prototypes marks that the biped robot has moved from a theoretical assumption to a practical entity, and has accumulated valuable experience for the subsequent technical improvement and functional expansion.

**(3) Rapid development stage**

Since the beginning of the 21st century, science and technology have witnessed rapid development, the level of hardware facilities such as computers and industrial manufacturing has been greatly improved, and intelligent robots have also appeared in the public's vision with the development of society. In different application fields, robots play their respective roles [18, 19]. In daily life, many families are equipped with sweeping robots, shopping guide robots and food delivery robots in shopping malls, in the field of manufacturing, many production lines are composed of mechanical arms, and in the field of logistics, there are intelligent warehouses composed of AGV robots. The emergence of robots can replace human work to a certain extent, especially in some areas with high repeatability and risk, which can not only reduce the risk of work, but also greatly improve work efficiency.

At the 2023 World Artificial Intelligence Conference, Tesla CEO Elon Musk said in a video that at some point in the future, the ratio of robots to humans may exceed 1:1, and humans will live in an era of abundance, where they can easily own any goods and services [20]. With the rapid development of computer technology and artificial intelligence industry, this moment is accelerating. Following the smart phone and smart car, robots have become a new representative of high-tech research, promoting the rapid development of control theory and control engineering, mechanical engineering, computer science, electrical engineering and other disciplines. Among all kinds of robots, biped robot is called the pearl on the crown because of its great difficulty and high value. Therefore, in November 2023, the Guiding Opinions on the Innovation and Development of Humanoid Robots put forward that by 2027, the technological innovation ability of humanoid robots in China will be significantly improved, and the comprehensive strength will reach the advanced level in the world, which indicates that the biped robot industry is in a golden period of vigorous development.

**3. Key technologies of biped robot**

**3.1 Mechanical structure design**

**(1) Leg structure**

The leg structure design of biped robot is the key to realize its flexible movement. Generally, each leg of biped robot has six degrees of freedom. The hip joint has three degrees of freedom, namely hip joint deflection, hip joint rolling and hip joint pitching. The knee joint has one degree of freedom, that is, the knee joint pitch. The ankle joint has two degrees of freedom, namely, ankle rolling and ankle pitching. Common types of leg structures are series and parallel. The serial joint structure simulates a plurality of joint movements of human legs by sequentially connecting a plurality of rotary joints from top to bottom, can provide larger movement space and flexibility, and is convenient to realize complex gait movements. However, the serial structure is easy to accumulate errors when transmitting motion from top to bottom, which requires high joint accuracy and control algorithm. The parallel structure has higher stiffness and bearing capacity, and the motion accuracy is relatively easy to ensure, but the motion space is relatively limited. In addition, there is a series-parallel structure, in which the ankle joint is designed as a parallel linkage mechanism, which is connected in series through the hip joint and knee joint. Compared with the traditional series structure, it has better motion performance.

In the actual design, it is necessary to consider the application scenarios and functional requirements of the robot, select the type of leg structure reasonably, optimize the joint configuration, simulate the kinematics characteristics of human legs as far as possible to meet the needs, and achieve stable and diverse walking, running and other actions.

**(2) Trunk and Balance Structure**

The trunk design of biped robot needs to consider many factors. First of all, we should pay attention to the structural strength and stability, ensure that it can bear the weight of each component and the dynamic force generated by the movement, and reasonably plan distribution of the center of gravity to meet the balance needs. At the same time, the degree of freedom and flexibility should be taken into account, and the corresponding movement ability should be given and the range of motion should be limited through the rational design of joints.

Reasonable mass distribution is the basis to ensure balance. Usually, the heavier parts are placed in the lower position as far as possible to reduce the center of gravity of the robot and improve its static stability. In addition, it will be equipped with auxiliary equipment such as gyroscope and balance adjustment device. The gyroscope can detect the posture change of the robot in real time, once the tilt occurs, the balance adjustment device will quickly restore the robot to the balance state by adjusting the joint angle and applying the reverse torque according to the feedback data of the gyroscope, especially when performing dynamic actions, this balance maintenance mechanism is particularly important.

In addition, from the perspective of ergonomics and appearance, the trunk shape should be ergonomic and beautiful to meet the needs of different application scenarios.

**(3) Foot design**

In terms of structural form, its shape needs to simulate the basic outline of human foot as far as possible, with a certain radian and a reasonable length-width ratio, which helps to better fit the ground in the process of walking, and achieve smooth support and transition. At the same time, the foot structure should have enough strength and rigidity to bear the overall weight of the robot, and will not be easily deformed or damaged in various motion postures, such as fast walking, jumping and other actions to reliably support the body.

In the selection of materials, both wear resistance and elasticity should be taken into account. The choice of wear-resistant materials can ensure that the surface of the foot will not be worn too quickly when it contacts and rubs with the ground for a long time, and maintain good performance. Proper elastic materials can play a buffer role when landing, and reduce the impact on the joints and the overall structure of the robot.

In terms of joints and degrees of freedom, the foot often needs to set up appropriate joints to give it certain mobility, such as flexion and extension, eversion and eversion at the ankle joint, so that the robot can flexibly adjust its foot posture when walking on uneven roads, stairs and other complex terrains, better adapt to terrain changes, and ensure the stability and fluency of walking.

In addition, anti-skid design should also be considered. By using special texture on the sole and adding anti-skid rubber pads, the friction between the foot and the ground is increased to prevent the robot from slipping in walking, turning and other actions, especially in wet, greasy and other special ground environments. In addition, in order to facilitate installation, disassembly and subsequent maintenance, the overall structural design of the foot should be relatively simple and modular, so that maintenance personnel can easily check and replace the parts of the foot.

**3.2 Motion control technology**

**(1) Kinematic modeling**

The precise motion control of the biped robot can be realized by kinematic modeling. Through forward kinematics, the position and attitude of the end-effector (such as the foot) of the robot can be calculated according to the known parameters such as the joint angle, while the inverse kinematics is to calculate the required parameters such as the angle and displacement of each joint in the case of the given target position and attitude of the end-effector. Based on the established kinematics model, the trajectory of the robot can be planned accurately. For example, in the process of walking, we can calculate the angle that each joint should reach at each step, so as to achieve the desired smooth walking or other actions.

**(2) Dynamic calculation**

Because the biped robot will be affected by its own gravity, inertia force, external forces and other forces in the process of motion, it is necessary to analyze the dynamic model of the robot and calculate the joint torque and other control variables needed to achieve specific motion. This enables the robot to adjust its motion state reasonably according to the actual force situation under different terrain and load conditions, so as to ensure stable and efficient motion. For example, when climbing, it can automatically increase the joint output torque to overcome the influence of gravity.

**(3) Gait planning**

Gait planning determines the way and rhythm of biped robot walking. Common gaits include static gait and dynamic gait. Static gait, such as flat gait, keeps at least one foot in contact with the ground during the walking process, and the center of gravity moves relatively smoothly, which is suitable for slower walking scenes. Dynamic gait allows both feet to leave the ground at the same time, like running gait, which can improve the speed of the robot, but requires higher balance control and coordination ability.

High stable walking ability is a necessary ability for biped robots, but compared with other robots, biped robots have high dimensionality and non-structural characteristics, so gait planning algorithm has been the focus and difficulty of biped robot research [7-11]. At present, the main gait planning algorithms for biped robots are: ① traditional model-based gait planning; ② bionics-based gait planning; ③ intelligent control algorithm-based gait planning. A pair of which is shown in table 1. In practical applications, it is necessary to select different gait planning algorithms according to the environment and task requirements to plan a reasonable gait in real time.

Table 1 Comparison of Gait Planning Algorithms

|  |  |  |  |
| --- | --- | --- | --- |
| Planning methods/evaluation indicators | Model | Bionics | Intelligent algorithm |
| Complexity | Low | High | High |
| Walking gait | Stable | Nature | Better |
| Hardware requirements | Low | High | High |
| Universality | High | Poor | Poor |
| Dynamics analysis | High | Poor | General |

**3.3 Sensor technology**

**(1) Attitude sensor**

Attitude sensors mainly include gyroscopes, accelerometers and so on, which are used to measure the attitude of biped robots. The gyro can accurately detect the angular velocity on each axis, while the acceleration sensor can detect the acceleration in all directions. Finally, the precise pose information is obtained by fusing the information of multiple sensors. When the pose of the robot changes, the controller will adjust the joints properly according to the feedback information, so as to ensure the stability of the robot when walking and walking.

**(2) Vision sensor**

Vision sensors such as cameras provide "eyes" for walking robots to observe the environment. Through image recognition and processing technology, robots can use vision sensors to identify obstacles, judge road conditions, and determine the location of targets. For example, in indoor environment, obstacles such as tables and chairs can be automatically identified through the images obtained by the camera, so as to formulate a reasonable walking route to avoid conflicts. At the same time, the vision sensor can also be used in target tracking, human-computer interaction and other aspects, which greatly expands the perception ability and autonomous decision-making ability of the robot.

**(3) Force sensor**

The soles, joints and other parts are equipped with force sensors, which can monitor the external stress state of the robot in real time. The force sensor on the sole of the foot can detect the size and direction of the ground force on the robot in the process of walking, so as to determine whether the distribution of the center of gravity of the robot is reasonable and whether the phenomenon of slipping occurs. Force sensors on the joint can feedback the pressure and torque applied by the joint, thus helping the control system to adjust the force of the joint, thus preventing joint injury caused by applying too much external force. It can also optimize the action of the robot, making the action of the robot more natural and coordinated.

**3.4 Human-computer interaction technology**

**(1) Voice interaction**

Voice interaction technology enables biped robots to have the ability of "listening" and "speaking". With the help of speech recognition algorithm, the robot can convert the received human voice instructions into corresponding operation instructions, and at the same time, through speech synthesis technology, it can respond to human beings with natural and fluent voice. In the service scenario, it can understand the needs of the guests and give accurate voice replies, which improves the convenience and friendliness of human-computer interaction.

**(2) Gesture recognition**

Using cameras, depth sensors and other devices, biped robots can realize gesture recognition. Through the analysis of the collected images or depth data, human gestures, such as waving, praising and pointing, are recognized, and these gesture information is translated into specific actions of the robot corresponding to the preset operation instructions.

**4. Application field of biped robot**

**(1) Industrial field**

In the industrial production environment, the advantages of biped robots are gradually highlighted. Compared with traditional wheeled or tracked robots, biped robots, with their flexible body shape and excellent balance ability, can freely shuttle in some areas with complex spatial layout, more obstacles or narrow passages.

In terms of material handling, biped robots can shuttle in a narrow and complex industrial environment by virtue of their flexible mobility, transporting raw materials and parts from warehouses to designated locations of production lines, or transporting finished products to storage areas. Compared with traditional handling equipment, biped robots can better adapt to complex terrain conditions such as steps and different ground materials, and can flexibly bypass or cross obstacles to improve the efficiency and accuracy of material handling.

In the equipment inspection work, the biped robot can regularly inspect all kinds of large equipment in the industrial plant, such as generator sets, large machine tools, automatic production lines, etc., according to the preset inspection route. It can use a variety of sensors carried by itself, such as vision sensors, temperature sensors, vibration sensors, etc., to monitor the appearance of the equipment, temperature changes, operating vibration and other key indicators in real time. Once abnormal conditions are found, the information will be quickly fed back to the control center, and the staff will be notified in time for maintenance, effectively reducing the loss caused by equipment failure.

In the field of assembly operations, biped robots can assist to complete some delicate and complex assembly tasks through precise action control and flexible posture adjustment. For example, in automobile manufacturing, to assist in the installation of some small and precise parts inside the automobile engine, or to carry out high-precision circuit board plug-in operations on the assembly line of electronic products, its multi-degree-of-freedom body movements can simulate human operation to ensure the quality and efficiency of assembly.

For some dangerous environment operations, such as industrial scenarios with high temperature, high pressure and toxic and harmful gases, biped robots can replace manual entry to perform tasks such as checking leakage points and shutting down faulty valves. It can withstand harsh environmental conditions, reduce the risk of casualties, and lay the foundation for subsequent troubleshooting and environmental remediation.

**(2) Service area**

In hotels, shopping malls, exhibition halls and other service places, biped robots are gradually becoming a new service force. As a guide, it can provide navigation information for customers through voice interaction and screen display, such as guiding customers to restaurants, exhibition halls, toilets and other locations. As a waiter, it can deliver goods for customers, such as tableware, drinks and so on in restaurants. This kind of service-oriented biped robot can not only improve service efficiency, but also add a sense of technology to the place and attract more customers. However, at present, its application in the service field still faces some practical problems, such as how to better avoid pedestrians and accurately identify customer needs in the complex flow environment, which still need to be further improved.

**(3) Rescue field**

Biped robots have great potential applications in disaster sites such as earthquakes and fires. Because of its ability to adapt to complex terrain environment, it can go deep into areas where human beings are difficult to reach or dangerous to search and rescue. For example, carrying equipment such as life detectors to search for survivors in collapsed buildings or delivering relief supplies to trapped people. However, in order to make it play a real role in the field of rescue, it is necessary to solve the reliability problems in harsh environments, such as dealing with high temperature, smoke, electromagnetic interference and other adverse factors, to ensure that it can work stably for a long time.

**5. Challenges faced by biped robots**

**(1) Motion control accuracy and stability challenges**

Although biped robots have made remarkable progress in motion control, there are still many difficulties to achieve high-precision and long-term stable motion in complex environments. On the one hand, the complex and changeable terrain in the real environment, such as wet and slippery ground, soft sand, uneven mountain roads and so on, will affect the walking and balance of the robot. It is difficult for the current dynamic modeling to accurately simulate all the forces in the actual environment, which leads to the phenomenon of instability in the process of motion. On the other hand, there is a certain delay in the real-time feedback control link, which makes the robot unable to make the optimal response to the sudden external interference in time, affecting the stability and accuracy of the movement, so it is necessary to further optimize the control algorithm and improve the response speed of the sensor.

**(2) Energy supply and endurance**

Biped robots consume a lot of energy, especially when they perform complex actions or work continuously for a long time. As the main way of energy supply, the existing battery technology has the problems of charging time and short endurance, which can not meet the requirements of long-term continuous operation of biped robots. This not only limits its application in some scenarios requiring long-term tasks, such as long-term industrial inspection, rescue search, etc., but also makes the design of robots need to consider how to optimize the energy consumption of motion under limited energy, such as reducing the resistance of motion by improving the mechanical structure and optimizing the motion control algorithm. However, these measures are still difficult to fundamentally solve the problem of energy endurance.

**(3) Intelligent and man-machine cooperation problems**

In practical application scenarios, efficient and safe cooperation between biped robots and humans is still a complex task. Firstly, robots need to have a higher level of intelligence to accurately understand human intentions, such as accurately distinguishing instructions for themselves in multi-person scenarios, and making reasonable speculations and inquiries in the case of fuzzy instructions. Secondly, in a dynamic environment, we should adjust our action plan in time according to the changes of the surrounding environment and tasks. However, the current artificial intelligence algorithms still have some limitations in dealing with these complex human-computer interaction and autonomous decision-making problems, and the human-computer interaction interface needs to be further optimized to improve the accuracy and convenience of information transmission.

**6. Development trend of biped robot**

**(1) Performance improvement**

In the future, biped robots are expected to achieve a significant improvement in motion speed, load capacity, and ability to adapt to complex environments. With the development and application of new high-strength and lightweight materials, the structural strength of robots will be further enhanced, while their own weight will be reduced, so that they can carry larger loads and achieve faster movement speed. In terms of control algorithms, more advanced dynamic and kinematic control algorithms will continue to emerge, enabling them to cope with various complex terrains and environmental changes more freely. For example, it can perform tasks stably and reliably in extreme weather conditions or complex field environments, and gradually approach or even surpass the ability of human action in the corresponding scenarios.

**(2) Intelligent integration**

Biped robots will be deeply integrated with artificial intelligence technology, not only in perception, decision-making, execution and other aspects to become more intelligent, but also better work with human and other intelligent devices. For example, through in-depth learning algorithms, it continuously improves its ability to perceive and understand the environment, and uses reinforcement learning to optimize its autonomous decision-making process, so that it can respond to various emergencies as flexibly as human beings. At the same time, robots are expected to form clusters to complete more complex tasks through mutual communication and cooperation, such as in large-scale disaster rescue sites, multiple biped robots cooperate to improve rescue efficiency and rescue scope.

**(3) Expand the application field**

The application of biped robots will continue to expand, in addition to the industry, services, rescue and other fields, it will also play an important role in space exploration, elderly care, education and entertainment. In space exploration, biped robots can assist astronauts to carry out scientific research missions on the surface of the moon, Mars and other planets by virtue of their ability to adapt to complex terrain; in elderly care, they can help the elderly to take care of their daily life and accompany them; In the field of education and entertainment, it can be used as interactive teaching AIDS, performance props, etc. To bring people a new experience, further develop its humanoid advantages, and create more value for human society.

**7. Conclusion**

After years of development, biped robot has gradually developed from the initial theoretical stage to an intelligent entity with powerful functions and application potential. In the course of its development, the key technologies are constantly breaking through, and the application fields are expanding day by day. However, it still faces many challenges, such as motion control, energy, human-computer cooperation and so on, which restrict its further wide application. Looking forward to the future, with the continuous progress of technology, biped robots are expected to make greater breakthroughs in performance, intelligence and application scope, better serve human society, and become an important force to promote the development of various industries. In the future, through the joint efforts of many researchers and related practitioners, biped robots will surely usher in a more brilliant development prospect.

**COMPETING INTERESTS DISCLAIMER:**

**Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.**

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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