The Research on the Method of Gait Planning for Biped Robot

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Abstract. Because of its great flexibility and high environmental adaptability, biped robot has been widely applied in many kinds of fields, including scientific exploration, daily service and so on. Biped robot, which has great potential both in social and economic aspects, is a cutting-edge research area in the field of robot study. In this manuscript, a humanoid gait planning method of biped robot based on the hip height and attitude compensation is proposed. Firstly, the sagittal and lateral kinematics models of the robot are established. The poses at critical moments in the process of walking of the robot are analyzed. At the same time, a complete gait planning is accomplished by using the cubic spline interpolation method, and the smooth trajectory obtained of each joint of the robot verifies the feasibility of the proposed method. Finally, the walking experiment is carried out to further verify the feasibility of the planning method.

Keywords: Biped robot · Zero Moment Point · Cubic spline interpolation · Gait planning

1 Introduction

The biped robot is a nonlinear system with multiple degrees of freedom, complex structure and strong coupling. As a result, it is a hot spot to achieve its stable walking control in the field of biped robot research [1]. The gait is the foundation of robot walking. The rationality of gait has a direct impact on the overall performance of the robot. So it is of great value to study the gait planning method and perform gait simulation in practice.

The biped robot has similar appearance and joint configuration to the lower body of human, and it is necessary for biped robot to have an anthropomorphic gait in order to be able to adapt to complex environment. Biomechanics studies show that, in the cycle of human's walking, the height of the hip is cyclical in the vertical plane and the hip has undulating movement in the horizontal plane in order to maintain body balance and reduce the energy consumption during walking. The traditional robot gait planning method assumes that the the height of hip joint remains constant and the robot torso remains perpendicular to the ground [2]. This assumption simplifies the robot pose model during walking to reduce the complex coordination between the degrees of freedom and reduce the amount of calculation in the planning process. Nevertheless, it

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does not accord with the human walking mode. This manuscript presents a gait planning method based on hip height and attitude compensation by studying the difference between human walking and traditional walking mode of robot. By establishing the sagittal and lateral kinematics models of the robot, analyzing the poses at critical moment during walking, the gait planning for the biped robot is completed with the help of cubic spline interpolation method. According to the simulation result by MATLAB, it can be found that the trajectory of each joint of the robot is smooth, which verifies the feasibility of the proposed method in theory. Compared with traditional method, this method shows an obvious advantage in lateral joint angle and lateral offset distance. Finally, experiments are performed, from which the feasibility of this method is verified in practice.

2 Mathematical Model of the Robot

The mathematical model of the biped robot is the foundation of the gait planning. A small steering gear biped robot with 10 degrees of freedom is studied in this manuscript (initial parameters shown in Table 1), which is shown in Fig. 1. Each leg has 5 degrees of freedom of rotation. Thereinto, the hip and ankle both have one sagittal and one lateral degree of freedom, while the knee only has a sagittal degree of freedom. For the reason that the axis of the ankle do not intersect with that of the hip, an eleven-bar mechanism model is established according to the structural characteristics of the biped robot, which is shown in Fig. 2.

Table 1. Initial parameters of robot

Number of joint	0	1(10)	2(9)	3(8)	4(7)	5(6)
Length (mm)	60	17	53	52	55	43
Mass (g)	288	95	32	138	32	84

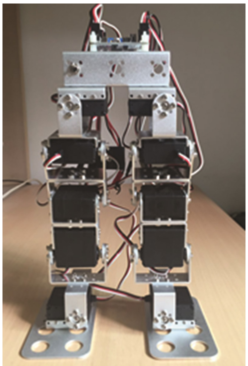


Fig. 1. Biped robot

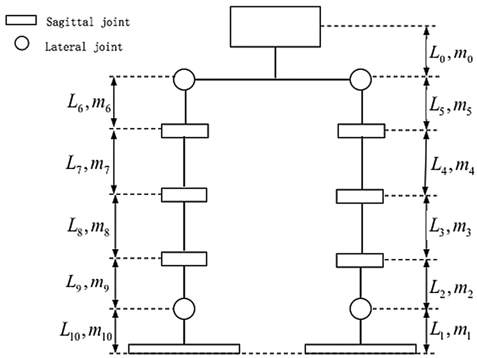


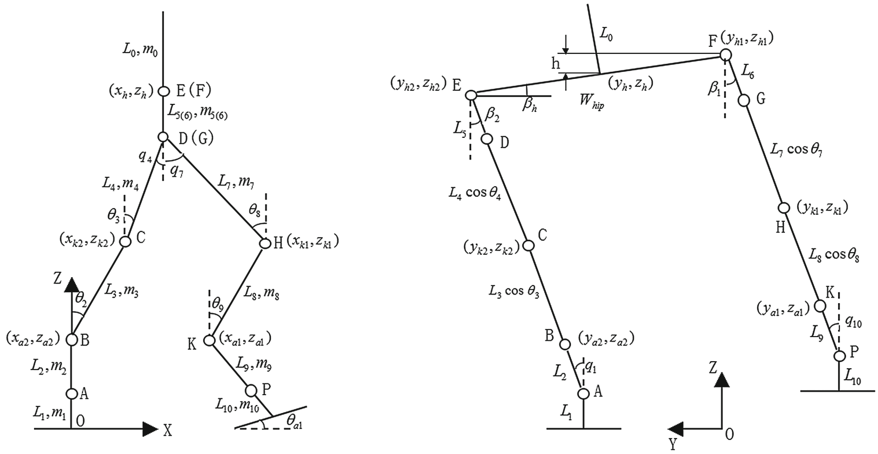
Fig. 2. Link model of Biped Robot

Kinematics analysis of biped robot is the prerequisite for the gait research. The purpose of kinematics modeling is to find out the kinematic relationship between the joints and the rigid body of the robot, which is the basis for gait planning [3]. The kinematics modeling of robotics includes forward kinematics and inverse kinematics modeling. With the geometric parameters of each rod of the robot and the angle of each joint, the forward kinematics can find out the position of each joint of the robot. The inverse kinematics can analyze the movement of the joint angles through the given position and orientation of the key part of the robot.

The biped robot has six sagittal joints and four lateral joints. As the motion coupling of the sagittal and lateral joints is small in the process of walking, the motion can be decoupled into sagittal and lateral movements and the influence of the lateral motion on the sagittal model can be neglected while the influence of leg bending on the lateral model while moving in the sagittal position is considered [4]. In addition, it can be considered that in the course of the movement, the robot's two feet do not finish any movement in the lateral direction.

The origin of the reference coordinate system is located at the junction of the lateral plane of the supporting leg's ankle joint, the horizontal plane and the radial plane of the center of the two hip joints. The direction of the X-axis is the sagittal direction of the robot, and the Y-axis is pointing to the positive direction of the left leg of the robot while the Z-axis is aligned vertically. The kinematic model of the robot is established, which is shown in Fig. 3(a) is the sagittal kinematic model, and (b) is the lateral kinematics model.

According to the kinematic model, the forward kinematics equation of the robot is obtained through geometric constrain. Then, the coordinates of the centroid of each link can be calculated. The first derivation and the second derivation are velocity and acceleration, respectively. Through the cosine theorem and the relationship between the angles of joints, each joint angle of the robot can be solved. The first derivation and the second derivation are angular velocity and angular acceleration, respectively. All of these provide the basis for the calculation of the ZMP (Zero Moment Point) of the robot.



(a) Sagittal model **(b) Lateral model**

Fig. 3. Kinematics model of robot

3 Gait Planning Method of Biped Robot

The gait planning includes two aspects: attitude planning and ZMP (Zero Moment Point) trajectory planning [2]. ZMP is currently the most widely used stability criterion in gait planning [5], which refers to the intersection point of the support surface and the extension cord of the resultant force of gravity and inertia force. The computational formula is as follows.

$$x_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)x_i - \sum_{i=1}^{n} m_i \ddot{x}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{1}$$

$$y_{ZMP} = \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)y_i - \sum_{i=1}^{n} m_i \ddot{y}_i z_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g)} \tag{2}$$

In the formula (1) and formula (2), m_i is the mass of each link, and (x_i, y_i, z_i) is the coordinate of the center of gravity of each link.

A gait generation method based on hip height and attitude compensation is presented in this manuscript. In this method, during the one-leg support period of the cycle, the height of the hip joint from the ground fluctuates within a certain range when the swing leg is swinging forward, and the maximum height value and the minimum height value are set in the planning process. Moreover, the left and right hip joints do not remain parallel, but swing up and down relative to the center of the two hip joints in the vertical direction.

The specific gait planning method is as follows. Firstly, according to the position and orientation of the main nodes of the biped robot at the critical moment, the trajectory of each joint throughout the gait cycle is planned by spline interpolation. Secondly, the ZMP of the robot is calculated and the hip trajectory optimization parameters within the appropriate range is traversed to find the maximum stability margin of the robot. Finally, after obtaining the optimal solution, the motion of the other joints is determined according to the kinematic equation of the biped robot, and the aim of walking stably is achieved.

3.1 Gait Planning

The walking process of the biped robot can be divided into three parts: the starting gait, the cycle walking and the stop gait. Figures 4, 5 and 6 show the radial and lateral poses of the biped robot at critical moments for these three kinds of gait, respectively. In the following figures, h is the maximum height of the swing of the hip in the vertical direction; k is the number of cycles; T_{sd}, T_{sm}, T_{sc} are the parameters for the starting gait; T_d, T_m, T_e are the parameters for the cycle walking. $T_{e0}, T_{ed}, T_{em,} T_{ec}, T_{ee}$ are the parameters for the stop gait; X_1, X_2 are the sagittal optimization parameters; y_1, y_2, y_3 are the lateral optimization parameters. Specific planning process is described as the below part. Starting: The biped robot moves from the upright state, lowering the height of the hip to the supposed height during walking, and the two hip joints are deflected by the lateral roll to the support leg; then the swing leg swings forward, and the two hip joints continue to move to the direction of the support leg. At the same time, the hip joint of the swing leg swings up relative to the center of the two hip joints, and the hip joint of the support leg moves downwards. The swing leg takes a step and then touches the ground. The hip re-parallels, and the starting state completes.

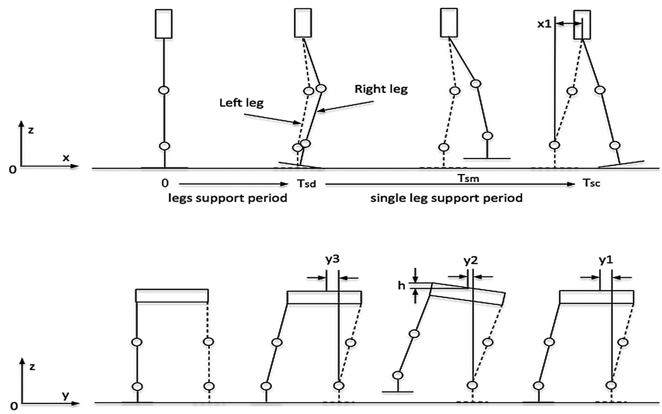


Fig. 4. Radial and lateral pose for the starting gait

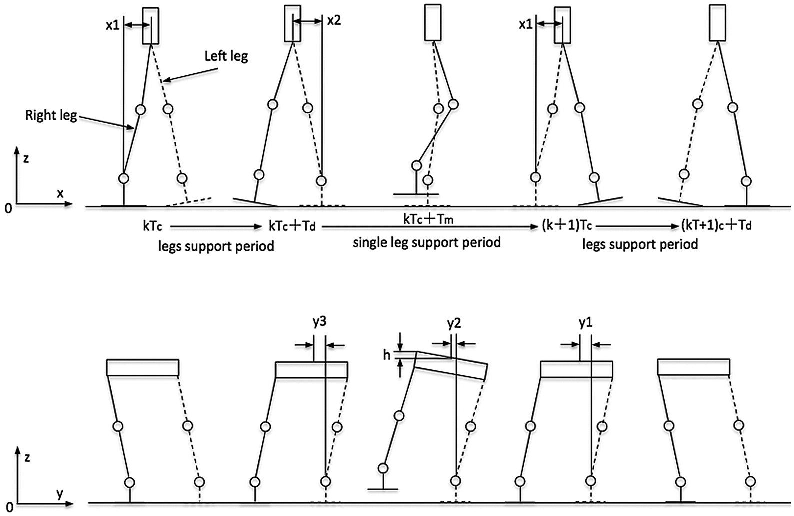


Fig. 5. Radial and lateral pose for the cycle walking

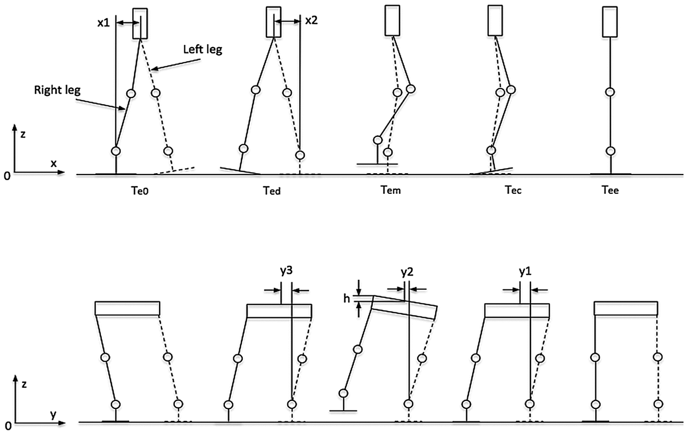


Fig. 6. Radial and lateral pose for the stop gait

Cycle walking: the robot walks according to the planned step, lift height, walking cycle and other parameters, and the travel speed remains constant. When the swing leg is swinging forward in the single leg support period, the left and right hip joints swing up and down relative to the center of the two hip joints. The hip joint corresponding to the swing leg swings up and then swings down. The hip joint corresponding to the support leg moves in the opposite direction. During cycle walking, the single leg support period and the two legs support period alternate periodically. Due to the symmetry of the robot and the periodicity of walking, if gait is planned in one cycle, then the robot can walk continuously.

Stop: the swing leg start leaving the ground, and the center of gravity of the robot is shifted to the support leg; Then the swing leg swings forward, and the two hip joints continue to move to the direction of the support leg; At the same time, the hip joint corresponding to the swing leg swings up relative to the center of the two hip joints, and the hip joint corresponding to the support leg moves downwards; The swing leg swings to the highest point; The swing leg takes a step and the hip re-parallels; The center of gravity of the robot moves to the center of two legs, and the center of gravity of the robot rises to the initial upright position. The stop state completes, and the robot stops moving.

The initial gait parameters are shown in Table 2. Due to the symmetry of the robot and the periodicity of walking, four cycles are taken to study in the complete walking process of the robot. The following x-axis range shows the whole trajectory cycle of robot in 14 s: 0–3 s for the starting gait, 3 s–11 s for the cycle walking, and 11 s–14 s for the stop gait.

Table 2. Initial gait parameters

Parameter	T_c	T_d	T_m	D_c	L_c	H_c	H_{max}	H_{min}
Value	2 s	0.5 s	1.2 s	85 mm	75 mm	20 mm	205 mm	195 mm

The foot movement trajectory obtained is shown in Fig. 7.

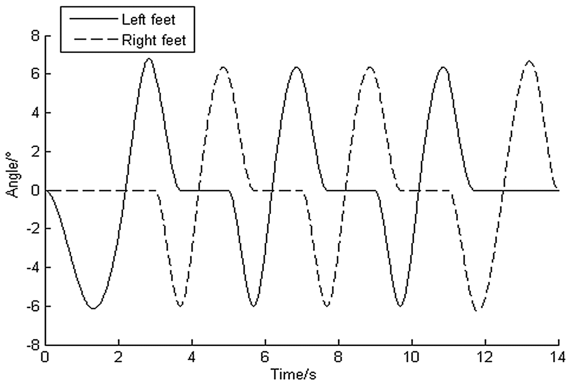


Fig. 7. Foot movement trajectory

The ankle trajectory obtained is shown in Fig. 8.

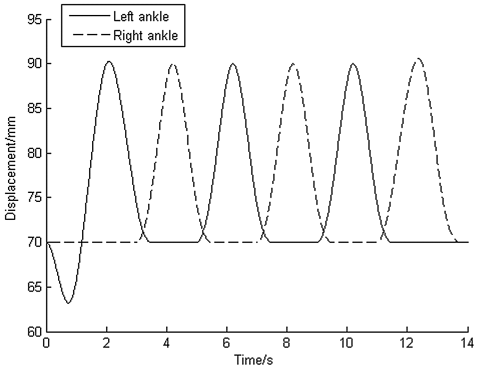


Fig. 8. Ankle trajectory in Z direction

The trajectory planning of the hip is critical to the robot gait planning. After planning the trajectory of the foot and ankle joint, as long as the completion of the hip trajectory planning, the variation curve of each joint angle can be solved through inverse kinematics equation, and finally the walking gait of robot can be obtained.

The hip trajectory obtained is shown in Fig. 9 (CTHJ refers to the center of the two hips). The trajectory of the center of two hips is a regular fluctuation curve. The left and right hip trajectories fluctuate up and down relative to the trajectory of the center of two hips, which conform to the laws of human walking.

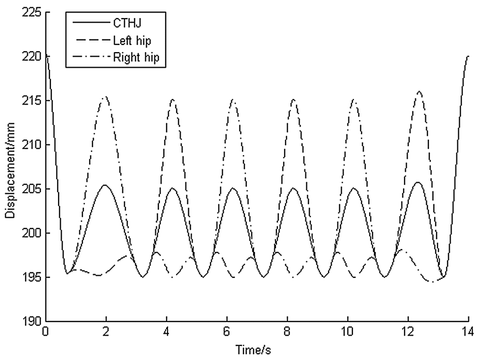
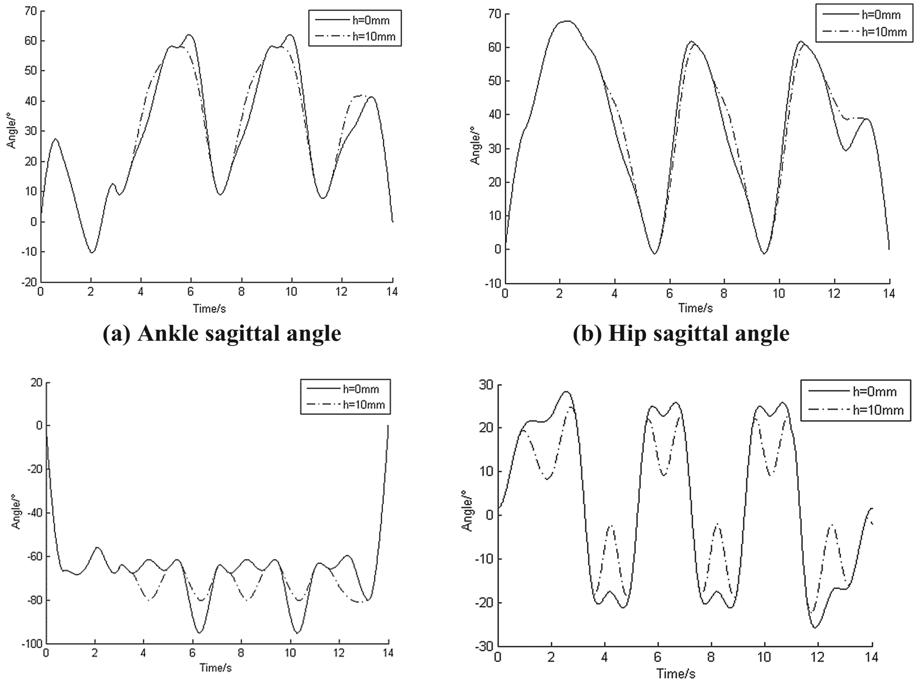


Fig. 9. Hip trajectory in Z direction

3.2 Gait Performance Analysis

The parameter h refers to the maximum distance that the hip joint swings up and down in the vertical direction. When $h = 0$, the two hips remain parallel; when $h > 0$, the two hips are parallel in the legs support period, and two hips swing up and down in the single leg support period. Two sets of data ($h = 0$ mm and $h = 10$ mm) are taken to contrastively analyze the effect of hip height and attitude compensation on lateral ZMP trajectory, lateral centroid trajectory and robot joint angle values. As is explained, when h = 0, the two hips remain parallel and it is exactly what traditional method assumes. When h = 10 mm, two hips swing up and down in the single leg support period, and it is exactly what the method based on hip compensation assumes.

Due to the periodicity of walking, the angle of the joint of the left leg is taken as an example to analyze the impact of the method based on the compensation of the hip joint on the joint angles. The joint angle values are shown in Fig. 10 (h = 0 and h = 10 mm).



(a) Ankle sagittal angle **(b) Hip sagittal angle**

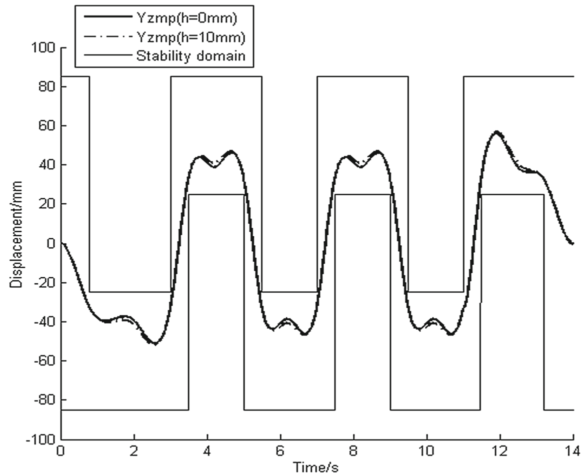
(c) Knee sagittal angle **(d) Hip lateral angle**

Fig. 10. Trajectory of each joint angle of robot

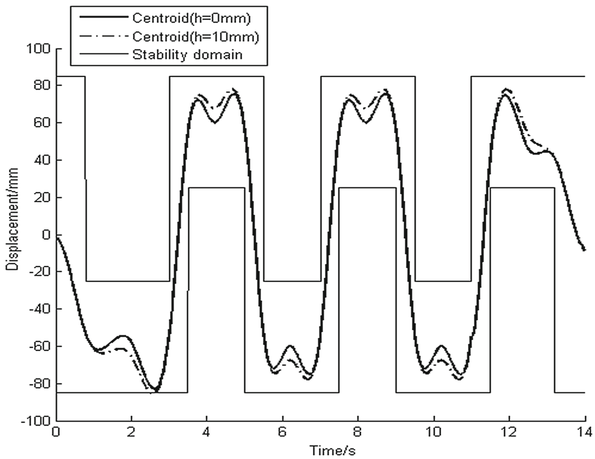
The joints of the robot have to move in a certain range to avoid the damage to the robot, so the maximum value of joint angle should be as small as possible. While the other gait parameters are same, the maximum forward angle value corresponding to h = 10 mm is smaller than that corresponding to h = 0 mm. Therefore, the planning method based on the hip compensation can protect the mechanical structure of the robot.

The lateral joint angle of robot is basically the same in the legs support period. But in the single leg support period, the lateral joint angle corresponding to h = 10 mm is smaller than that corresponding to h = 0 mm. That is to say, this planning method can reduce the lateral joint angle in the single leg support period, which is beneficial for the robot to walk steadily.

The ZMP trajectory and the centroid trajectory are shown in Fig. 11 (h = 0 mm and h = 10 mm). With the same gait parameters, the lateral ZMP trajectory and centroid trajectory corresponding to h = 10 mm are located in the outer side of these corresponding to h = 0 mm. This indicates that the swing of the hip can make the lateral ZMP trajectory and centroid trajectory move outward at the same lateral offset of the robot. Therefore, under the same lateral stability margin, the gait planning method based on the hip compensation can effectively reduce the lateral offset of the robot.



(a) Lateral ZMP trajectory



(b) Centroid trajectory

Fig. 11. Comparison of ZMP and centroid trajectories in the Y direction

4 Robot Walking Experiment

The angle values of each joint are transformed into the rotation angle of the steering gear to control the movement of the robot through the control software. Figure 12 shows the biped robot walking process which includes three parts: 0–3 s for the starting gait, 3–7 s for the cycle walking, 7–10 s for the stop gait. The robot is in upright state at the initial and end moment.

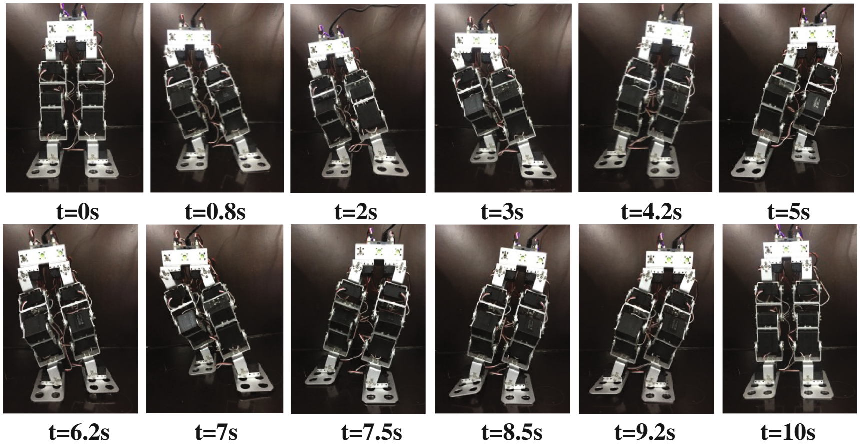


Fig. 12. Biped robot walking process

As can be seen from the figure, in the process of walking, the hip is always parallel to the ground in the legs support period, and the hip swings up and down in the single leg support period. The left and right legs alternately swing forward, and the robot gait meets the design requirements. Meanwhile steering gears run smoothly and the robot walks stably without any dumping or rollover.

5 Conclusion

In this manuscript, the mathematical model of the biped robot is given on the basis of D-H method. The trajectories of feets, ankles and hips are planned by the gait generation method based on hip compensation, and the angle of each joint is solved through inverse kinematics equation. The simulation results of MATLAB show that smooth trajectories can be obtained by this planning method, which proves that it is feasible. At the same time, under the condition of identical parameters, the impact of the hip compensation on the joint angle during walking is analyzed by comparing itself with the conventional planning method(h = 0 mm), and its regulating effect on the lateral ZMP trajectory and centroid trajectory is demonstrated. Finally, the robot prototype experiment is carried out to further verify the feasibility of the planning method. The experimental results show that the robot gait meets the design requirements and the walk movement is stable.

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