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Simulation Analysis of a Passive Biped Robot

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Abstract

To more accurately understand the fundamental characteristics of the motion of a passive biped robot and to enhance the guidance provided by model research for the design of practical prototypes, we analyze the characteristics of this passive model and establish the corresponding dynamic model using the Lagrange method. Based on the characteristic that the stable walking cycle gait of the robot manifests as a limit cycle in the phase plane, we study the passive biped model with knee joints through co-simulation using Adams and Matlab. The process of simulating steady-state walking of the ideal model is demonstrated in detail, including the initial conditions required for the robot to achieve periodic steady-state walking, the motion characteristics, and the distribution, variation, and interconversion of kinetic and potential energy during the motion.

Keywords

Passive Walking; Fixed Point; Biped Robot.

1. Introduction

The traditional research on biped robots mainly relies on the ZMP stability criterion [1] and the control methods of trajectory tracking used in industrial robots [2]. These conventional robots require a large amount of energy consumption, as well as complex trajectory planning and posture balance control. However, the complexity of the control systems and high energy consumption limit the feasibility of these robots in practical applications. In contrast, passive walking robots [3] are of great research value due to their structural and control simplicity, natural gait, energy-saving effects, and superior mobility in unstructured environments.

In 1989, McGeer [4-6] discovered that robots could achieve stable walking motion without the need for actuation and control, which introduced the concept of "passive dynamic walking." Since then, many scholars have been engaged in the research of passive robots. Significant achievements in passive robot research have been made by Cornell University [7], the Technical University of Munich [8], and the University of Twente [9]. Passive robots demonstrate natural gait and human-like walking energy efficiency, and studying passive walking helps to gain a deeper understanding of the essence of human walking [10-11]. However, the theory of passive robots is not yet fully mature, there are considerable differences between theoretical models and actual prototypes, and all analyses must be based on the premise that the robot can successfully walk.

2. Dynamics

The simplest passive walking robot model [12] established is shown in Figure 1. The biped walking robot with knee joints consists of four links connected by three rotational joints, forming an open-chain system. Each link has a non-zero mass and is uniformly distributed.

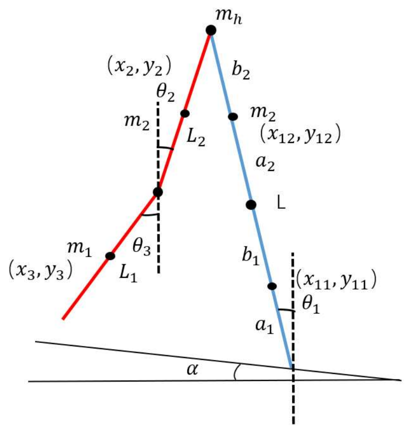

Figure 1. Schematic Diagram of Coordinate System Establishmen

To make the simulation feasible, the following assumptions are made:The legs are rigid, with no elastic deformation, and the hip joint is undamped and frictionless;The collision between the foot and the ground is idealized, assuming the curved foot does not deform or slip, and the collision is instantaneous, completely inelastic, with no slipping or bouncing;The ground is assumed to be rigid, flat, and has a small slope.

The entire motion cycle can be viewed as several phases depicted in the figure.

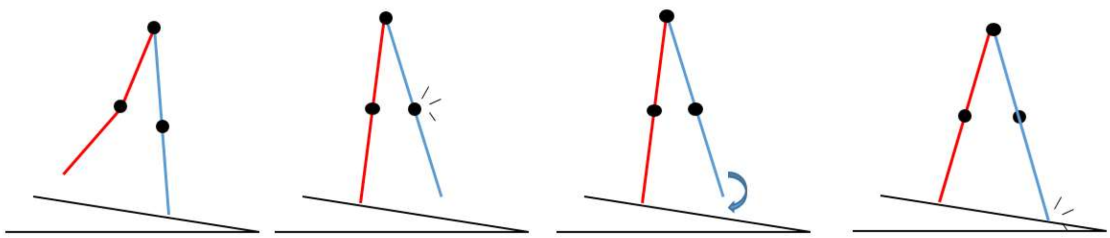

Figure 2. Presentation of different stages of walking

Given the initial conditions, this simple passive dynamic model can stably walk downhill on a small slope under the influence of gravity and its own inertia. Each step of the motion process can be divided into the following two parts:

Continuous dynamics during the unlocked knee stage: The robot's support leg remains straight, and there is no bouncing or relative sliding between the support foot and the ground. The knee joint of the swinging leg naturally bends and swings forward, with both the thigh and calf of the swinging leg moving forward. The Lagrangian function is established based on $L(\theta_1, \dot{\theta}_1) = K(\theta_1, \dot{\theta}_1) - P(\theta_1)$ to satisfy:

$$\frac{d}{dt}(\frac{\partial L(\theta_1,\dot{\theta}_1)}{\partial \dot{\theta}_1}) - \frac{\partial L(\theta_1,\dot{\theta}_1)}{\partial \dot{\theta}_1}) = \tau. \quad (1)$$

Since the biped walking robot with knee joints performs passive dynamic walking without any external force doing work on the robot, except for gravity, the right-hand side should be 0. Therefore, during the swing phase before the knee joint collision, the Lagrangian function should satisf. By establishing the Lagrangian equations for the point at the support foot and the point at the hip, and simplifying, the dynamic equations during the swing phase can be obtained as follows:

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$$M(\dot{\theta}_1)\ddot{\theta}_1 + C(\theta_1, \dot{\theta}_1)\dot{\theta}_1 + G(\theta_1) = 0. \tag{2}$$

where

$$\begin{cases} M_{11} = m_1 a_1^2 + m_2(l_1 + a_2)^2 + (m_h + m_1 + m_2)L^2 \\ M_{12} = -(m_2 b_2 + m_1 l_2)Lcos(\theta_2 - \theta_1) \\ M_{13} = -m_1 b_1 Lcos(\theta_3 - \theta_1) \\ M_{21} = -(m_2 b_2 + m_1 l_2)Lcos(\theta_2 - \theta_1) \\ M_{22} = (m_2 b_2^2 + m_1 l_2^2) \\ M_{23} = m_1 b_1 l_2 cos(\theta_3 - \theta_2) \\ M_{31} = -m_1 b_1 Lcos(\theta_3 - \theta_1) \\ M_{32} = m_1 b_1 l_2 cos(\theta_3 - \theta_2) \\ M_{33} = m_1 b_1^2 \end{cases}$$

$$\begin{cases} C_{122} = -(m_2 b_2 + m_1 l_2)L\dot{\theta}_2 sin(\theta_2 - \theta_1) \\ C_{133} = m_1 b_1 L\dot{\theta}_3 sin(\theta_3 - \theta_1) \\ C_{211} = -(m_2 b_2 + m_1 l_2)Lsin(\theta_2 - \theta_1) \\ C_{233} = -m_1 b_1 l_2 \dot{\theta}_3 sin(\theta_3 - \theta_2) \\ C_{311} = m_1 b_1 L\dot{\theta}_1 sin(\theta_1 - \theta_3) \\ C_{322} = m_1 b_1 l_2 \dot{\theta}_2 sin(\theta_3 - \theta_2) \end{cases}$$

$$\begin{cases} G_1 = -(m_h + m_1 + m_2)gLsin\theta_1 - m_1 g a_1 cos\theta_1 - m_2 g(l_1 + a_2)sin\theta_1 \\ G_2 = (m_2 b_2 + m_1 l_2)gsin(\theta_2) \\ G_3 = m_1 g b_1 cos\theta_3 \end{cases}$$

During the continuous dynamics of the locked knee stage, after the knee impact, the knee will remain locked and the system transitions to a double-pendulum structure. At this point, the straight leg continues to swing, and the dynamic equations can be obtained as follows:

$$M(\dot{\theta}_1)\ddot{\theta}_1 + C(\theta_1, \dot{\theta}_1)\dot{\theta}_1 + G(\theta_1) = 0. \tag{3}$$

Where

$$M = \begin{bmatrix} M_{11} \ M_{12} \\ M_{21} \ M_{22} \end{bmatrix}$$

$$C = \begin{bmatrix} 0 \ c \\ -c \ 0 \end{bmatrix}$$

$$G = \begin{bmatrix} -(m_h + m_1 + m_2)gLsin\theta_1 - m_1 g a_1 cos\theta_1 - m_2 g(l_1 + a_2)sin\theta_1 \\ (m_2 b_2 + m_1(l_2 + b_1))gsin(\theta_2) \end{bmatrix}$$

$$\begin{cases} M_{11} = m_1 a_1^2 + m_2(l_1 + a_2)^2 + (m_h + m_1 + m_2)L^2 \\ M_{12} = -(m_2 b_2 + m_1 l_2)Lcos(\theta_2 - \theta_1) \\ M_{21} = -(m_2 b_2 + m_1 l_2)Lcos(\theta_2 - \theta_1) \\ M_{22} = (m_2 b_2^2 + m_1 l_2^2) \\ \mathrm{c} = (m_2 b_2 + m_1(l_2 + b_1))Lsin(\theta_1 - \theta_2) \end{cases}$$

ISSN: 2710-0588

When the swing leg touches the ground, a collision event occurs, known as the heel strike phase. Subsequently, the swing leg and the support leg switch roles, completing an entire gait cycle and re-entering the dynamics of the double-pendulum mechanism.

3. Adams-MATLAB Simulation

Due to the passive robot being a complex nonlinear dynamic system, simplifying the robot's structural parameters and walking environment parameters is necessary when establishing its dynamic mathematical model. First, a simplified robot model needs to be created using SolidWorks. The designed robot model is then added to the ADAMS simulation. By setting degrees of freedom, contact force parameters, gravity parameters, etc., a more realistic experimental environment can be obtained. Therefore, the model is imported into ADAMS for simulation. As shown in Figure 3, this is the ADAMS simulation model of the aforementioned robot.

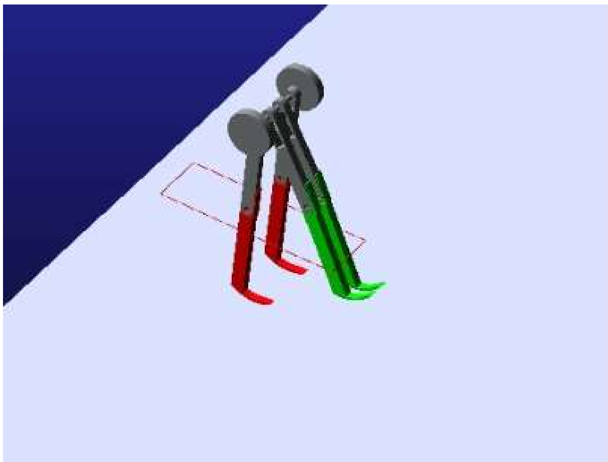

Figure 3. Adams Simulation Model

Adams Simulation Settings for the robot, utilizing the widely used IMPACT contact force model: Stiffness set to material stiffness. Generally, higher stiffness values make integration more challenging; too low stiffness fails to capture realistic contact conditions. Here, it is set to 10^8. Force exponent typically set to 1.5 or higher. Range is ⩾0; for rubber, values like 2 or even 3 are used, while metals commonly use 1.3 to 1.5. Damping defines the damping properties of the contact material. Values are ⩾0; for some rubber and metal materials, typically 10^4 N·s/m is used. Penetration depth defines the penetration value under full damping. When penetration is zero, damping coefficient is also zero; ADAMS/Solver employs a third STEP function to solve between these points. Range is penetration depth ⩾0; for general metals and rubber materials, it is set to 10^4 m.
The geometric parameters of the designed model are listed in Table 1.

Table 1. Robot structural parameters

Single leg mass /kg	Thigh length /m	Shank length /m	Foot radiu /m	Hip joint linkage length /m	Hip joint mass /kg
2.23	0.22	0.25	0.5	0.2	4.2

Nonlinear systems are extremely sensitive to initial conditions, and the only controllable aspect is the initial conditions. The subsequent motion is a predictable passive motion. For a passive dynamic walking robot, taking the moment when both feet are on the ground and a collision

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has occurred as the initial state, the initial conditions of the robot must meet stringent requirements. The initial angle and angular velocity of the robot's swinging leg should, after completing a full gait cycle, closely match those of the previous step to achieve periodic walking motion. The initial state can be represented by three independent parameters, specifically $\emptyset_{01} = (0.3059, 0.142, 0.144)$ Simulation curves were generated in Adams-Matlab co-simulation, as shown in Figure 5.

Figure 4 and Figure 5 reflects the curve changes of the model's motion during the first 10 steps, showing that the model gradually stabilizes after the initial few steps of adjustment. From Figure 4, it can be seen that the angular displacement of the swinging leg varies significantly, while the angular displacement of the supporting leg changes less. When the two legs coincide, the angular displacement is greater than zero, indicating that the legs overlap on the left side of the vertical position on the slope. The angular displacement curve of the swinging leg during one cycle shows that when the swinging leg leaves the ground, it first undergoes a backward swing, then swings forward, and finally falls back to collide with the ground. From Figure 5, it can be seen that the angular velocity of the supporting leg is always less than that of the swinging leg. The angular velocity of the swinging leg varies widely, changing from negative to positive and then decreasing back to negative; whereas the angular velocity of the supporting leg is always negative, indicating that the supporting leg is always moving forward. When the legs collide, the absolute value of their velocities decreases simultaneously, indicating a reduction in the robot's kinetic energy at that moment.

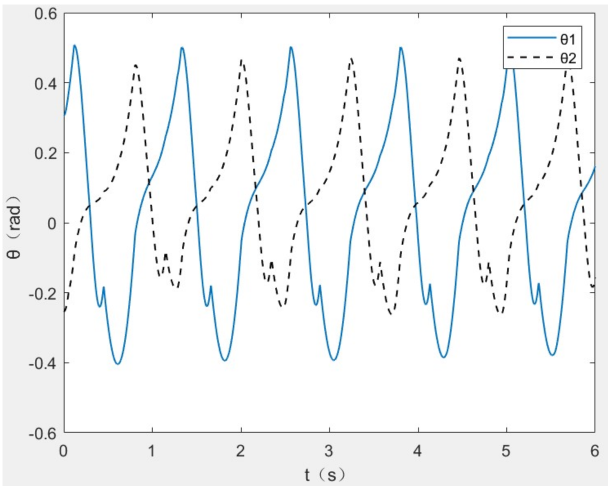

Figure 4. The motion curve of the leg angles over time

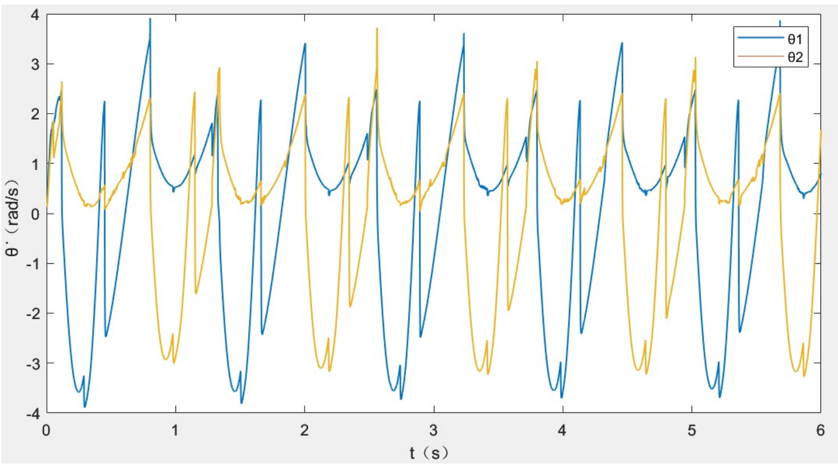

Figure 5. The variation curve of the leg angular velocities over time

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The periodic gait of biped walking robot with knee joint can be represented by the limit cycle diagram on the phase plane. Figure 6 is the limit cycle diagram of the periodic gait of a biped walking robot with knee joint. The swinging leg of the biped walking robot with knee joint has just left the ground at all times: the thigh and calf of the swinging leg of the biped walking robot with knee joint have moved in a straight line at all times: The whole process from time A to time B is a continuous leg swing stage. The knee joint of the swinging leg of the robot can move freely and swing forward until the thigh and calf of the swinging leg move in a straight line, The knee joint of the swinging leg of the robot collids from time B to time C, and the spatial configuration of the robot does not change, but the angular velocity changes, and the knee joint of the swinging leg is locked. From time C to time D, it is still a continuous leg swing stage, and the robot's swinging leg swings to the maximum angular displacement, and then swings back until it sends a collision with the ground. From time D to time E, the foot of the robot's swinging leg collides with the ground. At this time, the Angle does not change but the angular velocity changes. After a cycle, it converges into the same coil to form a "limit cycle", which reflects the stable gait of the robot.

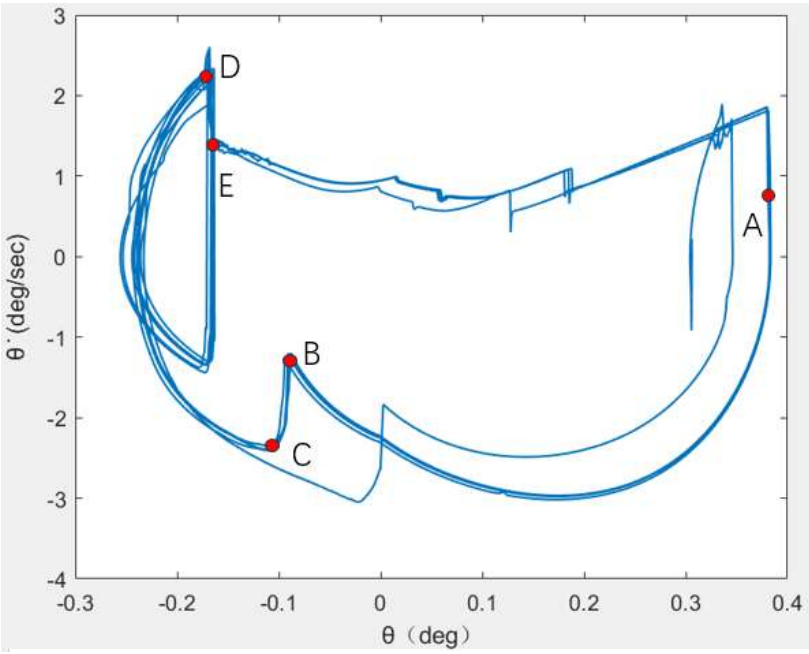

Figure 6. limit cycle

Figure 7 illustrates the changes in kinetic energy, potential energy, and total mechanical energy of the model during the motion process from an energy perspective. As shown in the figure, within one step, the kinetic energy first decreases, then increases, decreases again, and finally increases once more, while the potential energy exhibits the opposite trend. This indicates a coupling relationship between the swinging leg and the supporting leg. The kinetic energy at the end of each step is almost the same as at the beginning of that step; the potential energy at the end of each step decreases in an almost arithmetic progression, approaching the potential energy at the beginning of that step.

During the swinging phase of each step, since only gravity is doing work, the total mechanical energy remains conserved. During the collision phase, the kinetic energy changes suddenly while the potential energy remains unchanged, leading to a reduction in the total mechanical energy. In a complete gait cycle, the work done by gravity on the system equals the kinetic energy lost due to collisions.

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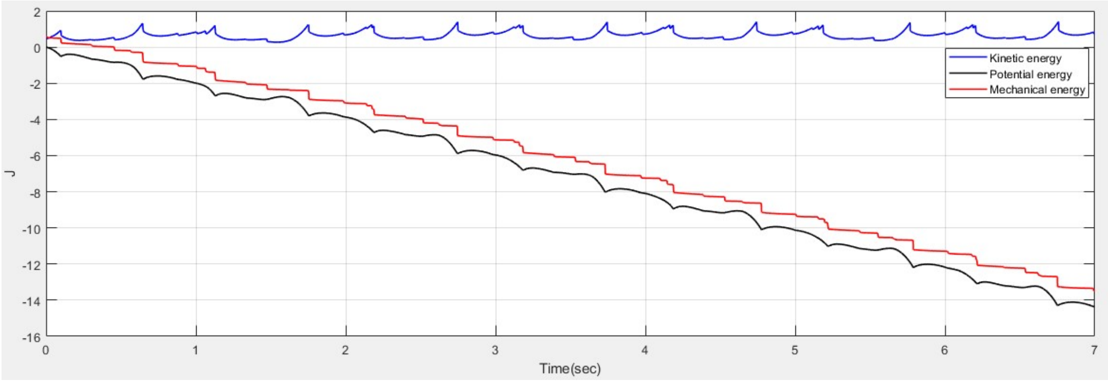

Figure 7. Energy Change Curve During Exercise

4. Conclusion

The mathematical model of the walking gait of a passive biped robot was established using the Lagrange method. Through Adams-Matlab simulation analysis, the initial conditions for the idealized model to walk, its motion characteristics, and the energy changes during the motion process were obtained, reflecting the essential characteristics of biped robot motion. The simulation provided parameters such as leg length, mass, and center of mass position, laying the foundation for the eventual construction of a physical prototype that successfully walks on the road.

References

[1] Kajita S, Nagasaki T, Kaneko K, et al. ZMP-based biped running control[J]. IEEE robotics & automation magazine, 2007, 14(2): 63-72.

[2] Yin X, Pan L. Enhancing trajectory tracking accuracy for industrial robot with robust adaptive control[J]. Robotics and Computer-Integrated Manufacturing, 2018, 51: 97-102.

[3] Wisse M, Feliksdal G, Van Frankenhuyzen J, et al. Passive-based walking robot[J]. IEEE Robotics & Automation Magazine, 2007, 14(2): 52-62.

[4] McGeer T. Passive dynamic walking[J]. The international journal of robotics research, 1990, 9(2): 62-82.

[5] McGeer, Tad. "Passive walking with knees." Proceedings., IEEE International Conference on Robotics and Automation. IEEE, 1990.

[6] McGeer, Tad. "Passive bipedal running." Proceedings of the Royal Society of London. B. Biological Sciences 240.1297 (1990): 107-134.

[7] Collins, Steven H., and Andy Ruina. "A bipedal walking robot with efficient and human-like gait." Proceedings of the 2005 IEEE international conference on robotics and automation. IEEE, 2005.

[8] Renjewski, Daniel, et al. "Exciting engineered passive dynamics in a bipedal robot." IEEE Transactions on Robotics 31.5 (2015): 1244-1251.

[9] Dertien, Edwin. "Dynamic walking with dribbel." IEEE Robotics & Automation Magazine 13.3 (2006): 118-122.

[10] Wu Haoxian. Research on Standing Balance Control of Passive Ankle Joint Humanoid Robots [D]. Zhejiang University, 2016.

[11] Zhou Liang. Research on Efficient and Energy-saving Underdetermined Bipedal Biomimetic Walking Machines [D]. Jilin University, 2018.

[12] Ikemata, Yoshito, Akihito Sano, and Hideo Fujimoto. "A physical principle of gait generation and its stabilization derived from mechanism of fixed point." Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.. IEEE, 2006.