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# Gait Planning and the Cost of Transport of Biped Walking

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**ABSTRACT**
The study aims to build an accurate biped model, design a suitable controller and analyze the cost of transport of biped walking. A three-mass model restricted to moving in a two-dimensional plane using PID controller and gait planning was established as the dynamic model based on the Lagrange equation. And a calculation method of robot energy consumption based on impulse is proposed to analyze the cost of transport. Some indexes such as stability,the cost of transport and so on are used to compare two controllers: using PID controller only and both using PID controller and gait planning. External perturbations are forced to verify robustness. The simulation results indicate that the robot stabilizes more quickly and consumed less energy when both using PID controller and gait planning than using PID controller only. In addition, the robot has certain adaptability to external disturbance.

**KEYWORDS**
Biped model; Lagrange equation; PID; Gait planning; Cost of transport

## 1 Introduction

Biped robot has human appearance characteristics and walking ability, so it can adapt to human living and working environment. Compared with traditional wheeled robots, legged humanoid robots have obvious advantages because they may replace or assist humans in adverse environments. Developing a robust biped robot has been investigated for decades and it is still challenging in the robotic community. Besides, energy consumption is another problem. The smaller the cost of transport, the higher the energy efficiency of the robot.

To make the balance between computational complexity and model accuracy, the three-mass model is presented (T. Sato, S. Sakaino and K. Ohnishi 2010). In this model, mass of the swing leg and mass of the stance leg are considered to improve the accuracy of modeling.To achieve walking on level ground, active drive system is required and numerous controllers are created, one of which is PID controller, one of the earliest developed control strategies. PID control are applied to each joint to control joint angels of biped robots (Rakesh Gautam; Akshay T Patil 2015). In addition, stable and natural gait is the main sign that biped robot is different from other types of robots. And accurate trajectory planning directly determines the stability and coordination of biped robots, required driving torque and the cost of transportation. Low energy efficiency is one of the important factors restricting the practicability of biped robots. At a certain walking speed, the robot can have countless controllers, but the energy consumed by the robot system is different when realizing required gait patterns so it is necessary to analyze energy consumption.

In this paper, we established a three-mass biped model restricted to moving in a two-dimensional plane using PID controller and gait planning to plan the gait. And a calculation method of robot energy consumption based on impulse is proposed to analyze the cost of transport. The simulation results applied on an actual biped robot show that a stable limit cycle can be formed and the proposed method is effective and feasible.

## 2 Methodology

### (1) Robot description

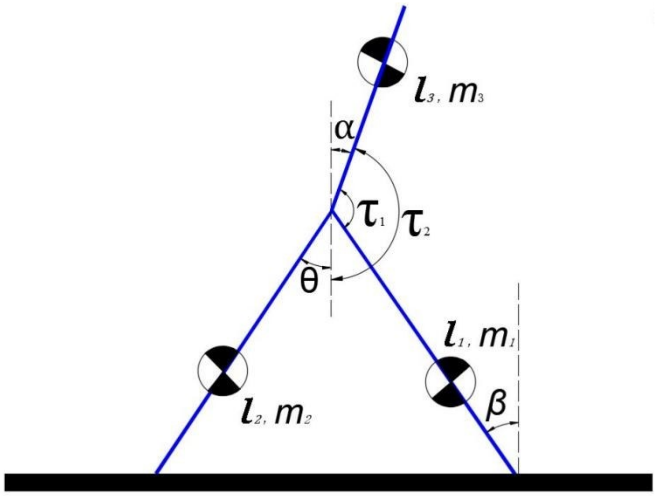


Fig.1 model of the robot

The model shown in Fig.1 is a three-mass model restricted to move in a two-dimensional plane. The torso is a rigid rod with length of $L$ and a center mass of $m_3$. The length of both legs is $l_2$ and $l_2$. And the center masses of both legs are $m_2$and $m_3$. Joint torque $\tau_1$ and $\tau_2$ are used to control $\alpha$ and $\beta$.

### (2) Lagrange equation of robot dynamics

The dynamic equation is established by Lagrange equation. Lagrange equation is

$$L = K - P \tag{1}$$

Where $K$ is the kinetic energy of the system and $P$ is the potential energy of the system.

The dynamic equation is

$$\frac{\mathrm{d}}{dt}\left(\frac{\partial L}{\partial q_i}\right) - \frac{\partial L}{\partial q_i} = 0, i = 1,2\ldots n \tag{2}$$

Where $n$ is the degree of freedom of the system and $q_i$ is the variable of the system.

### (3) Implementation of PID Controller

The general form to implement a PID controller on a system can be give as following:

$$\tau = K_p e + K_d e + K_i \int e \tag{3}$$

Where $e$ is the error and $K_p$, $K_d$ and $K_i$ are the proportional, derivative and integral gains respectively.

## (4) Gait planning

In order to ensure certain accuracy, some high-order polynomials are used to interpolate the selected feature points. However interpolation using higher-order polynomials often produces ill conditioned results. At present, there are many ways to eliminate morbidity. In these methods cubic spline interpolation is a method with less calculation and better accuracy. So cubic spline interpolation is used to make the change at the joint angels smoother.

## (5) Cost of transport

Jun Nishii gave a method of definition of legged locomotion energy consumption according to the joint torque and angular velocity of a leg in 2006. But this equation does not consider the energy consumption of the robot even when maintaining a certain configuration, that is, when the motion speed of some or all joints is zero, so it is not accurate enough.

So the cost of transport is defined based on impulse in this paper：

$$CoT = \sum_{i=1}^{n} \int_{0}^{T} |\tau_i| dt \tag{4}$$

Where $n$ is the number of joints of the robot, and $\tau$ is the driving torque of the joint.

From the perspective of energy, the formula is that the total impulse of the input system is directly proportional to the energy consumed to maintain the motion of the robot, so the definition is reasonable.

# 3 Simulation and Results

## (1) Stability

Figure 2 shows the change of joint angels using PID controller only and Figure 3 shows the change of joint angels using PID controller and gait planning. We can see from figures that in the initial stage of gait movement, the angle of each joint changes greatly, but it shows a stable periodic cycle in the later walking stage. It is noticeable that $\beta$ stabilized more quickly when using both PID controller and gait planning than using PID controller only.

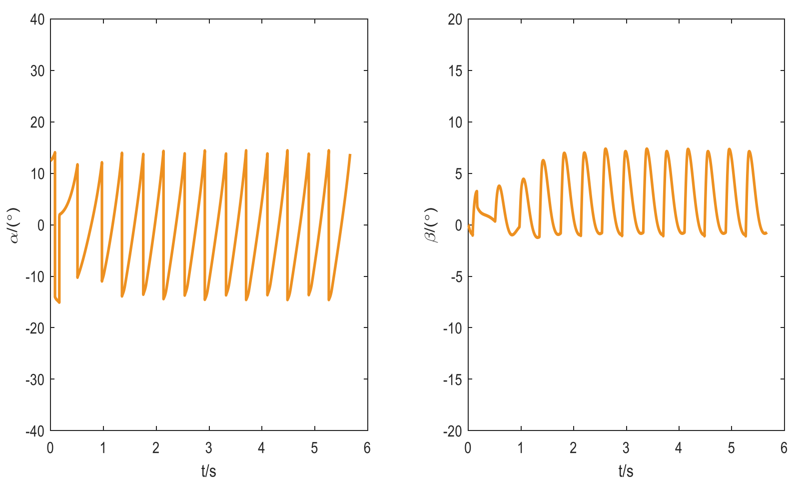


Fig.2 the change of $\alpha$ and $\beta$ using PID controller only

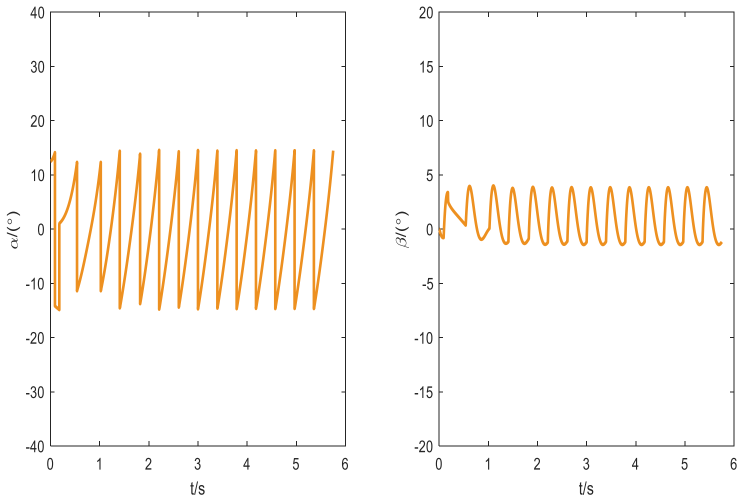


Fig.3 the change of $\alpha$and $\beta$ using PID controller and gait planning

## (2) The cost of transport

According to the image curves of joint torque, the torque of each joint changes periodically, and the stable output torque can ensure the stability of the robot. From the analysis of the actual input torque, we can know that, when using PID controller and gait planning, the fluctuation of the actual control torque of the joint is relatively small, the input torque is relatively smooth, and the motion of the foot robot is more stable. The cost of transport is definitely smaller when using PID controller and gait planning because the total impulse of the input system is directly proportional to the energy consumed to maintain the motion of the robot. Energy consumption comparison is shown in Figure 6.

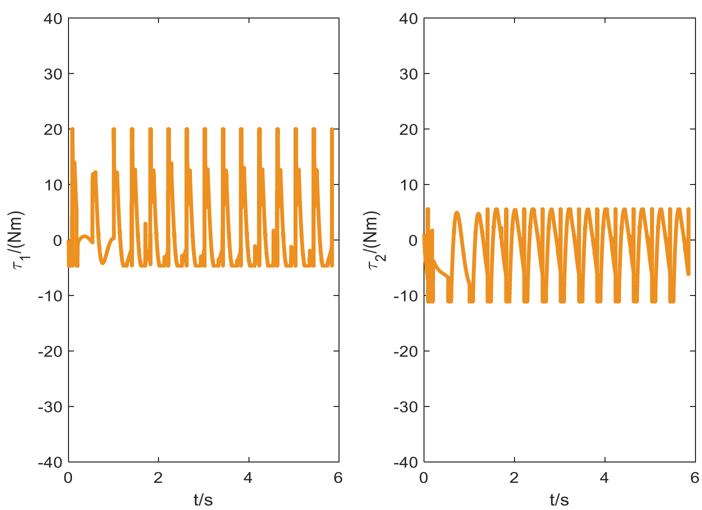


Fig.4 input torque using PID controller only

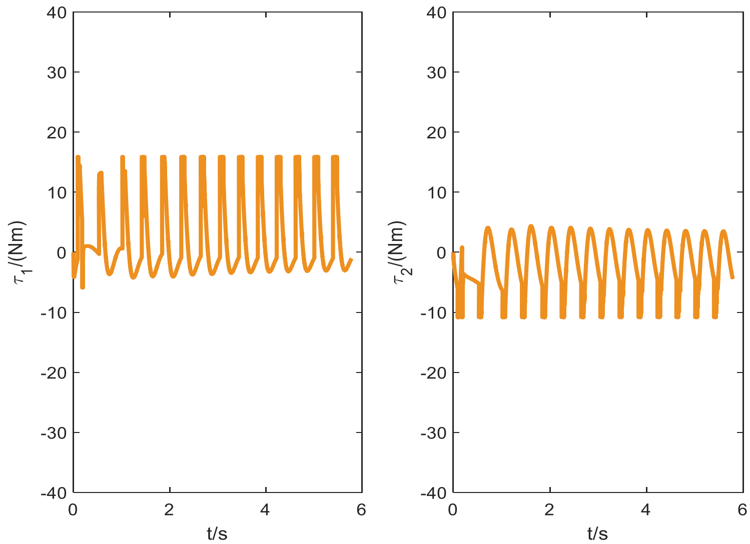


Fig.5 input torque using PID controller and gait planning

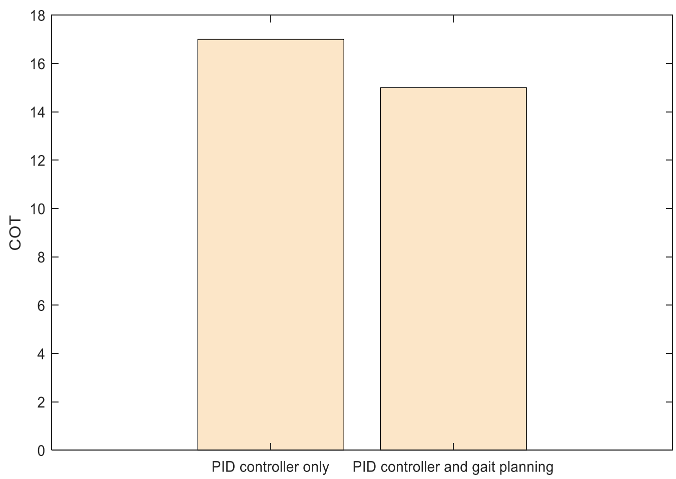


Fig.6 the cost of transport using PID controller only and using PID controller and gait planning

## (3) Robustness

In order to verify the robustness of robot dynamic walking under disturbance when both using PID controller and gait planning, the robot withstands external perturbation and the intensity is $F = 10N$, 20% of the gravity. The simulation results are shown in Figure 7. It can be seen that joint angels $\alpha$ and $\beta$ both converge to a stable limit cycle, which shows that the controller has certain adaptability to the external disturbance.

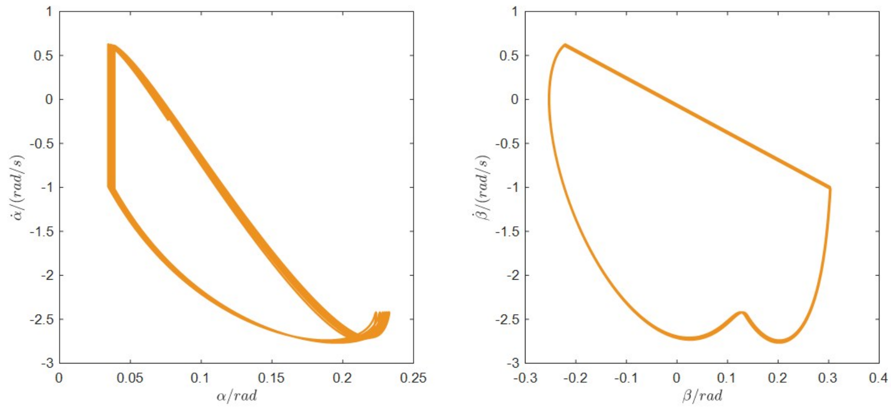


Fig.7 limit cycles of $\alpha$ and $\beta$

## 4 Conclusion

The study built a biped model to plan the gait and analyze the cost of transport of biped walking. A three-mass model restricted to moving in a two-dimensional plane is used as the dynamics model based on Lagrange equation. The cubic spline interpolation method is used as the gait planning strategy. The energy consumption is calculated by the equation based on impulse. Significant differences were discovered in stability, the cost of transport and so on between using PID controller only and both using PID controller and gait planning. The robot also withstands external perturbation to verify robustness. The simulation results validated the performance and robustness of the proposed model.

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