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# Central pattern generator control system research of humanoid robot's smooth walking

**Xiaodong Tan*, Yanlei Lei, Dongxu Liu**

**School of Mechanical Engineering, Dalian Jiaotong University, Dalian, (CHINA)**

**E-mail: txd_f@sina.com; leiyanlei0501@126.com; liudongxu@163.com**

## ABSTRACT

This research is combining Central Pattern Generator approach and advantages of passive dynamics. In this research the smooth walking problem of the large mass torso biped walking robot is solved. The core innovation is a direct, robust and efficient control system which is developed through designing a five-level reflex controller. In this paper we introduce some new methods: Using a simple sine function as output torque waveform of CPG controller to drive the motor which links the swing leg and the hip joint; Impose secondary incentives to improve the landing performance of swing leg when it is unbending; Design a pedal foot kinetic energy regulation controller according to the different walking of robot; Design a feedforward discretization torso controller to reduce the swinging amplitude of torso. Through simulation tests in Matlab/Simulink, our strategy for large mass torso biped walking is verified.



## KEYWORDS

Biped walking;
Passive dynamics;
Limit cycle;
CPG control;
Large mass torso.

## INTRODUCTION

For the biped walking robot with large mass torso, adding a torso in the biped walking models requires extra effort because the torso needs to maintain stability in the moving process through motor control. Torso dynamics is very similar to the instability of the inverted pendulum itself. In addition, the hip joint, base of the unstable torso, moves in space. The acceleration of the hip joint causes a large disturbance to the torso balance in walking. Despite these challenges, human beings are still able to maintain the torso in the sagittal plane within the offset of only 0.02 radians (about 1 degree), and it also can significantly reduces the angular velocity of head relative to crotch. Professor Chatterjee and others proposed a completely passive robot with torso which can move at a certain speed[4] on the flat ground. Professor Gomes and Ruina developed a walking model[5,6] with no energy dissipation at a certain speed. The supporting leg moves with the way of an inverted pendulum, while collision of swing leg causes kinetic energy loss, which must be compensated through incentives. However, if the robots have a torso, as long as the torso and the swing leg are not in a straight line in landing, there is no total loss of kinetic energy. So adding a torso can reduce the energy dissipation rate in collision.

In this paper, we study the active control of torso posture and the coordination control of torso stability and walking stability with the use of CPG control in limit cycle walking.

## SIMULATION MODEL

This simulation model is based on a simplified walk model of Garcia, shown in Figure 1. We can see a rigid 2D model of 3-4 rigid rod alternating, in which a torso with a length l4=0.6 and two legs linked in the crotch with a unit length l1=0.6. Each leg has a coelongate thigh and calf, that is l2=l3=0.3. In addition each leg also has a rigid circular foot with a radius 0.2 and an opening angle 120 °. There are five mass points in the model. One is torso mass point as m4 = 3.3, and other two are thigh mass point as m2 = 2.2 as well as two calf mass points as m3 = 1.1. When a full leg is in a straight line, the mass points of thigh and calf will be merged into the mass point of the full leg as m1 = 3.3 with a negligible quality of foot. The relative size and relative quality, we proposed here, are a rough abstraction of the actual principle prototype quality size distribution, which we are going to develop. The model walks in a gravitational field with g acceleration of gravity. The torque between two legs of hip joint is u2, and the torque between supporting legs and torso is u1. In the model, the unilateral constraint between foot and ground is a rigid constraint.

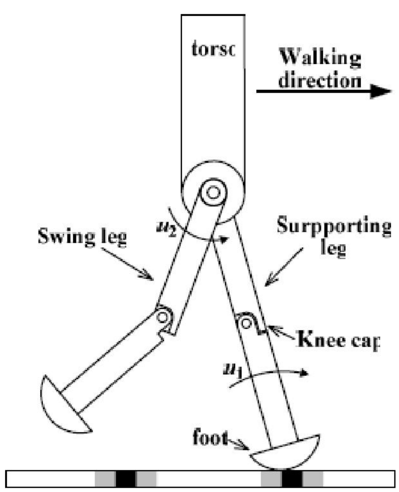


**Figure 1 : Robot reality model**

Several pre-assumptions of simulation gait are as follows (see Figure 2):

1) Gait is made of two steps. One is Single leg supporting, and another is momentary two legs supporting.
2) The supporting legs remain straight during the walking.
3) The swing legs have completely straight before landing.
4) The impact is completely inelastic collision when thigh and calf are in a straight line.
5) The collision of swing leg landing is also completely inelastic collision.

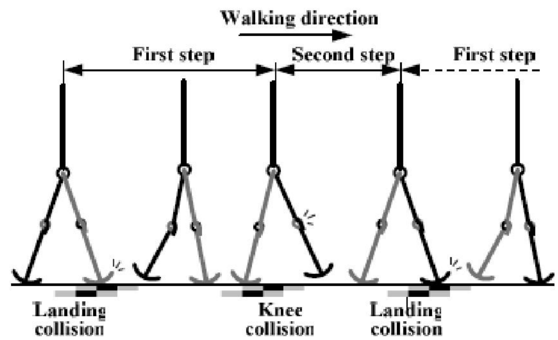


**Figure 2 : Model walking strategy diagram**

The coordinates and parameters of system refer to Figure 3 and TABLE 1.

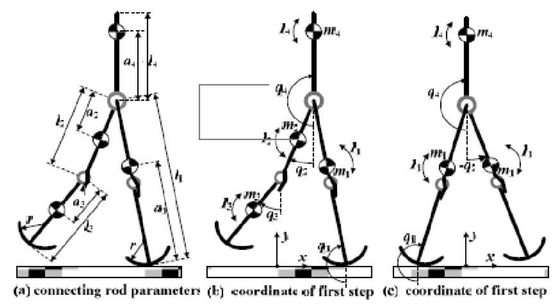


**Figure 3 : Model connecting rod parameters and coordinates**

## CONTROLLER DESIGN

### CPG basal controller

Biological studies have revealed that movement of vertebrates, including humans, mainly generates and regulates by Central Pattern Generator (CPG), rather than brain. Central Pattern Generator (CPG) is a biological neural circuit to generate animal rhythmic movement behavior, which consists of a series of neural oscillator, and is a complex distributed neural networks integrated by neural oscillator and multi-reflector loop system. The instructions of animal rhythmic movement could be independently generated by the CPG, and it could produce a stable movement pattern by nerve – muscle coupled and motion perception feedback system, to make the animal rhythmic movement pattern with a better adaptability and plasticity.

**TABLE 1 : Specific parameter list of model**

| Model parameter | unit | rod | symbol | value |
|---|---|---|---|---|
| quality | kg | leg | m1 | 3.30 |
| | | thigh | m2 | 2.20 |
| | | calf | m3 | 1.10 |
| | | torso | m4 | 3.30 |
| length | m | leg | l1 | 0.60 |
| | | thigh | l2 | 0.30 |
| | | calf | l3 | 0.30 |
| | | torso | l4 | 0.60 |
| | | Feet radius | R | 0.20 |
| mass point moment of inertia | $m^2kg$ | leg | I1 | 0.123 |
| | | thigh | I2 | 0.032 |
| | | calf | I3 | 0.016 |
| | | torso | I4 | 0.016 |
| mass point position | m | leg | a1 | 0.35 |
| | | thigh | a2 | 0.14 |
| | | calf | a3 | 0.16 |
| | | torsi | a4 | 0.2 |

CPG basal controller designed here is based on the above bionic idea, providing a most basic walking style and gait for biped walking, so we called it basal controller. We use a most simple rhythmic signal - sine wave as stride driving torque of swing leg, that is

$$u_2(t)=\begin{cases} A\cdot\sin\phi+B, & T_G^i<t\le T_K^i \\ 0, & T_K^i<t\le T_G^{i+1} \end{cases}$$

In which $\phi=\omega\cdot(t-T_G^i)+\phi_0$ $T_G^i$ and $T_K^i$ respectively represent the moment of landing collision and knee collision of the i-th step. $\phi_0$ is a initial phase angle of oscillator. CPG basal controller is controlled by a sensor input signal, shown in Figure 4. Knee impact signal and landing impact signal obtained by the contact sensor collaboratively control the start / stop state of crotch oscillator. This intermittent control strategy bases on the human body EMG signal measurements. Through the above design, the number of CPG controller parameters is much less than the number of existing neurons oscillator method, which also reserves some working place for crotch secondary incentive.

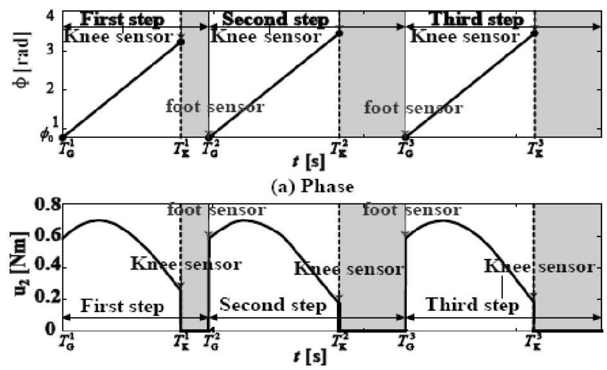


**Figure 4 : Output signal diagram of CPG basal controller**

## Feedback Torso PD controller

The controller is designed to achieve the inverted pendulum control of torso, that is, keeping torso upright as possible during walking. $u_1$ and $u_2$ respectively represent the torque of supporting leg and swing leg relative to torso. Therefore, $u_2-u_1$ represents the torque $u_{torso}$ suffered by the torso. For , we design a simple and direct PD controller, shown as the following equations, in which the gravity of the torso should be ahead basing on the bionics, will be set at 7.5 °.

$$\begin{cases} u_2=A\cdot\sin[\omega\cdot(t-T_G^i)+\phi_0]+B \\ u_2-u_1=-K_P(q_4-\pi-\phi_{bias})-K_D\dot{q}_4 \end{cases} \Rightarrow \begin{cases} u_2=A\cdot\sin[\omega\cdot(t-T_G^i)+\phi_0]+B \\ u_1=K_P(q_4-\pi-\phi_{bias})+K_D\dot{q}_4+u_2 \end{cases}$$

We can see, due to the addition of torso control, swing legs not only bear a reaction of swing torque, but also bear a reaction of torso PD torque control, that is, torso control take an impact on the coordination walking of two legs. We should choose a reasonable value for two parameters KP and KD. If the value of the parameters is too small, the system rigid will be not enough, and then the torso will sway violently. It not only can't meet the technical specifications of torso control, but also makes more difficult to the walking stability of system. If the value of parameters is too large, it will generate a sharp pulse in landing impact, and the amplitude of which may be higher an order of magnitude than CPG sinusoidal signal. So if there is a slight disturbance, it will be difficult to maintain the walking stability of lower body.

## Feedforward grid torso correction controller

The controller is designed to reduce the torso motion range, to improve the stable movement indicators of torso. Especially before swing legs landing, let robot torso leaned forward in advance. On one hand it can buffer the suddenly back of landing. On the other hand it also can increase the angle between torso and back extension line of swinging leg to reduce energy loss resulted by shock. This control strategy, base on the bionic, simulates the waist muscles and joints rhythmic movement of human walking. Theory and experiment have been fully confirmed. Specific controller design is as follows:

After a stable walking of robot, we find that in each walking, during the time from swing legs lifting to landing, supporting legs swing over a angle about 0.24 radian. We take it as a measure of robot walking process, and per 0.03 radian as a node we can classify the whole robot walking process into 9 pieces. At the j node of the i step, we can detected the deviations between current running status and expected results, that is, the deviation of torso angle $q_4$ and torso angular velocity $\dot{q}_4$ relative to standard angle respectively is 7.5 ° and 0 rad / s :

$$Bias_{i,j} = q_4 - \pi - 10 \times \pi / 180 + \dot{q}_4 / 80 + Bias_{i-1,j}$$

The reason why we take the bias angle of 10 ° rather than 7.5 ° is just because we take into account that the risk of torso backwards to system is much larger than torso forward. So in the forward correction process we slightly increase the torso forward range with the use of bias. In addition, we also hope to get a convergent control strategy through cumulative deviation, to prevent a control oscillation.

Then at the j-1 node of the i +1 step we start a given correction based on the walking experience of previous step, to achieve the feed-forward pre-correction:

$$\tau_{rect(i+1,j-1)} = 10 \times Bias$$

This correction torque will continue until the j node of the i+1 step, and then measure $Bias_{i+1,j}$ by the same method. And so the cycle continues, the first node of new step is the tenth node of previous step. So it accomplishes the discrete sampling and analysis of movement state information t, the raster processing of full movement, and the whole tracking of movement correction. This method can effectively reduce the complexity of control strategy, dramatically reduce the amount of computation, effectively capture the motion information, and provide an effective feedforward control for the torso control of robot motion control system.

## Feedback pedal foot controller

The controller is designed to add energy for biped walking system. The problem of the system without torso is not obvious in this respect. But for the control system with torso, due to large mass torso, energy loss increases in landing collision and the gravitational potential energy need to be supplemented also increases in barycenter shifting. So the addition of pedal foot to supplement energy loss is very necessary.

Shown in Figure 5, the direction of pedal foot impulse designed here is upward along supporting legs, acting at the moment of swing legs landing.

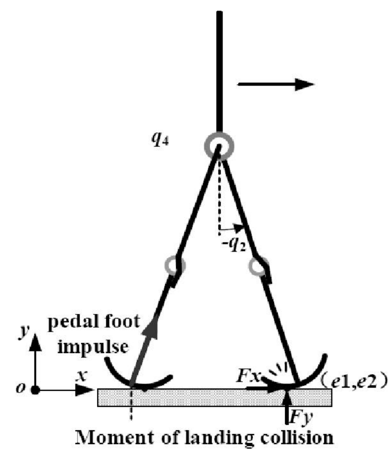


**Figure 5 : Pedal foot impulse diagram**

Research shows that this pedal foot impulse added to robot system will not affect walking frequency of robot system, and increase the pace and improve the energy efficiency of walking. Since the stride of each step can reflect potential energy and kinetic energy of a system to some extent. Hence we take the stride of one step as measured standard. The value of specific impulse is determined as follows:

$$I_{push-off} = \begin{cases} 0 & \theta_{span} > 0.245 \\ 0.2 & 0.245 > \theta_{span} > 0.240 \\ 0.21 & 0.240 > \theta_{span} > 0.2315 \\ 0.3 & 0.2315 > \theta_{span} > 0.230 \\ 0.5 & 0.230 > \theta_{span} > 0.220 \\ 0.37 & 0.220 > \theta_{span} > 0.210 \\ 1.5 & 0.210 > \theta_{span} \end{cases}$$

In which the value is the best results obtained through several tests. There was abnormal in case 6 just because we specifically consider robot doesn't into a stable walking in the first three steps.

### Feedforward half swing Leg controller

The controller is designed to monitor the motion state of half walking for the compensation control especially kinetic energy and momentum. Through the secondary incentive of crotch torque, we can control the walking stride, improve the position of swing legs landing, and adjust the kinetic energy and momentum of system. If only for the thigh angular position of swing legs, due to the poor immunity of system, a small deviation can easily be enlarged. So we directly chose to analyze the thigh angular velocity so that we can have a more directly control to kinetic energy and angular momentum. When the supporting legs perpendicular to ground, that is, we take parameters measurement at half time of walking process and further propose a control strategy.

Specific secondary incentive torque as the following equation:

$$\tau_{\sec ondary} = \begin{cases} 0.2 & 0.25 > \dot{q}_2 > 0.15 \\ 0.15 & 0.15 > \dot{q}_2 > 0.08 \\ 0 & 0.08 > \dot{q}_2 > 0.02 \\ -0.2 & 0.02 > \dot{q}_2 > -0.07 \\ -0.3 & -0.10 > \dot{q}_2 > -0.135 \\ -0.4 & -0.135 > \dot{q}_2 \end{cases}$$

We respectively design CPG basal controller, feedback torso PD controller, feed-forward grid torso correction controller, feedback pedal foot controller, and feed-forward half swing leg controller. Five controllers cooperate with each other, and respectively mimic the action of human walking such as pedaling the feet, swinging the torso and so on, as well as reflective adjustment of specific motion state. They collectively make up a reflection control system together based on the CPG principle.

## CONTROL SYSTEM SIMULATION RESULT ANALYSIS

For the CPG control system combined by five controllers, we take a simulation on the model of robot dynamics and controller models with use of Matlab / Simulink, to assess the effect of this control strategies and make relevant conclusions, as follows:

### Each joint angle and angular velocity analysis

Figure 6 shows each joint angle diagram of robot from the beginning of walking into the stable. We can see that the system can make a quick adjustment to ensure a stable walking after three steps instable walking at the beginning.

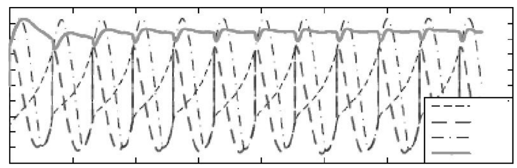

**Figure 6 : Angular position of each joint during robot walking**

Figure 7 shows each joint angular velocity of robot from the beginning of walking into the stable. We can see that the angular velocity mutation of torso can receive a quick rectify after landing.

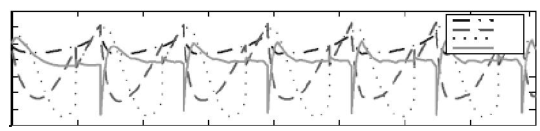

**Figure 7 : Angular velocity of each joint during robot walking**

Figure 8,9,10 respectively shows the joint angles and angular velocity of swing leg and supporting leg within thirty seconds. All of these figures are clearly reflects the limit cycles formed after stable walking of robot. It shows a stable and reliable walking of robot.

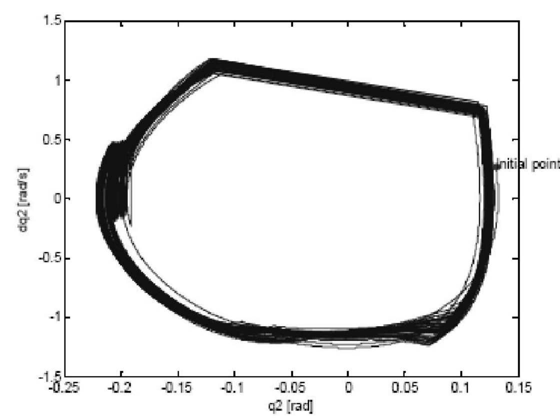


**Figure 8 : Limit cycle diagram of supporting leg**

### Control effect analysis of the torso

Figure 11 shows a angle and angular velocity diagram of torso. We can see that although the graph is not as neatly as the swing legs', but it still appears a clear and stable limit cycle and a high repeatability graph style.

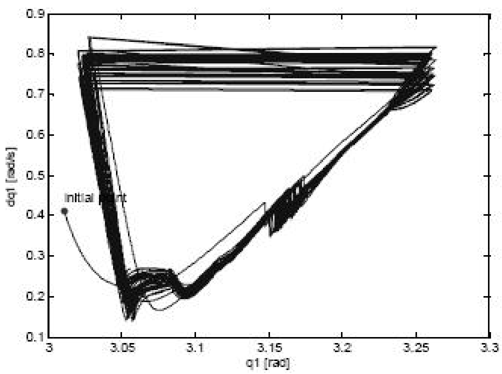


**Figure 9 : Thigh limit cycle diagram of the swing leg**

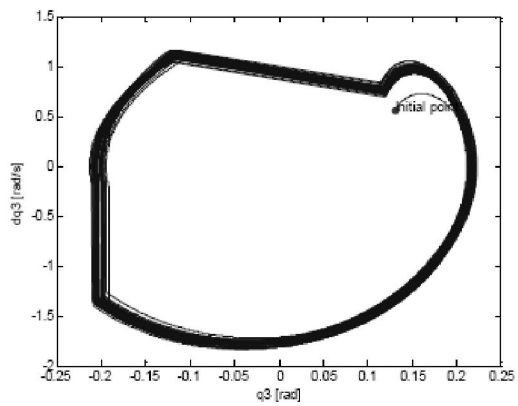


**Figure 10 : Calf limit cycle diagram of the swing leg**

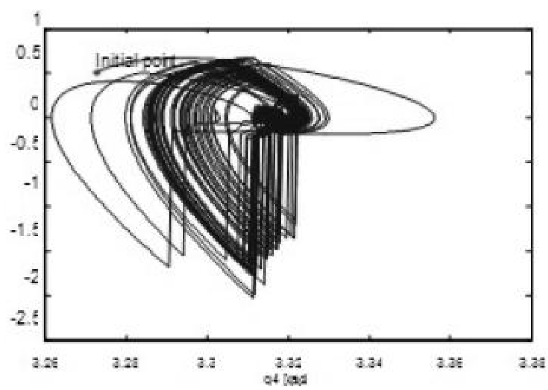


**Figure 11 : torso swing limit cycle diagram**

Maintaining torso stability is a key in this study, because keeping stability of torso during walking is a prerequisite for a stable visual platform, and it is important to the study of humanoid robots in the future. The access we take to this technology index assessment is by means of extracting the standard deviation of torso angular displacement $\theta_b$ in walking (Time of pace is T).

$$||\theta_b||_2 = \sqrt{\frac{1}{T}\int_0^T (\theta_b - \bar{\theta}_b)^2 \cdot dt}$$

Through the graph of q4, we can see that the swing range of torso correspondingly decreases after a correction of raster torso feed-forward control system. Through the numerical analysis of simulation results, we get a torso swing range with every 5 seconds doing one index evaluation. The results we obtained

as follows:

Through the above measurement data, it shows that the raster torso feed-forward control system successfully plays a role in reducing the swing range gradually in order to achieve the effect of convergence, and the torso swing range takes in a good tendency of gradual weaken. The technology index we obtained, especially the index 0.0048 during the 25th - 30 seconds, is superior to 0.0052 of Dutch delft university of technology Hobbelen group, which takes a major study in related fields[8]. The maximum torso swing range 0.02 radian is better than 0.04 radian of Hobbelen group. The formulation of whole torso control strategy and the specific controller design is very successful.

### Whole walking effects analysis

As shown in figure 12, it shows a walking stick diagram of robot walking 30 seconds 49 steps. We can see that the whole walking of robot is smooth and stable, and the system we design can satisfies the technical requirements. Specific 30 seconds video of successful walking could download from the URL:

http://166.111.4.50/personaldata/2006010583/s30. avi.

The simulation results shows, the system we design, collectively combined by CPG basal controller, feedback torso PD controller, feed-forward grid torso correction controller, feedback pedal foot controller, and feed-forward half swing leg controller successfully realize the passive walk control with large mass torso, torso swing range in a reasonable range, and a stable and smooth robot walking.

## CONCLUSION AND OUTLOOK

The motion control of large mass torso mainly lies in the torso coordination and legs coordination, namely the key of main control is, on one hand how to realize the inverted pendulum control of torso, on the other hand how to maintain a stable biped walking influenced by inverted pendulum control. Compared with original system without torso, which gives priority to pose control and emphatically analyzes the angle of each joint, passive walking institution with large mass torso gives priority to the motion state control and emphatically analyzes angular velocity of each joint. In the system without torso, it controls the speed and position of supporting legs to coordinate energy conversion, whereas in the system with torso, it emphatically controls the dynamic situation of swing legs, improves swing legs landing conditions in order to prevent the subtle error is amplified swing legs, improves swing legs landing conditions in order to prevent the subtle error is amplified.

In this paper, CPG basal controller imitates the walking control characteristic of human nerve center; feedback torso PD controller, feed-forward grid torso correction controller imitates the waist rhythmic movement of human walking, which has important significance to the walking balance and torso visual platform stability; pedal foot controller imitates the action of pedal foot or knee bounce motion to supplement kinetic energy during human walking or running; feed-forward Swing leg controller imitates human walking to improve landing performance, to prepare instinctive responses for the next step. The whole constitute walking control system effectively imitates the control strategies of human walking, with a fully confirmation on the simulation model of large mass torso. Especially the technical indexes of torso control meet the requirements of system.

Future follow-up work can be started as the following:

1). The walking control strategy research of the system with large mass torso on the rough pavement.

2). The variable-step range or variable-step frequency control strategy research of the system with large mass torso on the flat pavement.

3). The specific impact of the control parameters of large mass torso system to walking

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