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Biped Blind Walking on Changing Slope with Reflex Control System

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***Abstract*—This paper presents a novel reflex control system for passive biped walking on unknown slope varying terrains by extension of previous work in the fields of CPG. The algorithm takes advantage of the passive dynamics of walking, assisting only when necessary with an intermittent oscillator driving the hip joint. We analyze inherent reasons of falling for a biped system based on dynamic principles and assume that human walking relies more on instinct actions within the spinal cord rather than brain. Corresponding falling tendency function is proposed, based on which a reflex controller adjusting output of oscillator is designed. An auxiliary span angle controller is put forward to provide secondary actuations for compensation to improve landing performance. The proposed reflex system requires no prior knowledge of the terrain or tens of hundreds of experiments, which are necessary for machine learning methods. Results of simulations indicate that our reflex controllers are capable of ensuring stable passive blind walking on slope varying terrains without ankle torque.**

I. INTRODUCTION

Passive dynamic principles have aroused a new trend of researches hoping to realize stable, limit-cycle legged walking with low energy cost. However, purely passive walkers, which require no actuation or active control, have rigorous requirements of initial conditions for each step to be completed. Meanwhile, minor perturbations like changes in terrains tend to break the limit cycle and cause falling. Consequently, researches have been taken to provide active control methods towards the problem of walking on varying terrains. Among them, machine learning methods are very promising and become the mainstream. However, since machine learning methods are based on the principles of trials and errors, large amounts of experiences are required to realize the exploration of terrains and law of walking. With no prior knowledge of the terrain, those machine learning methods can not ensure immediate blind walking in an unknown environment.

On the other hand, biological investigations suggest that locomotion in vertebrates, including humans, is mainly generated within the spinal cord rather than brain, by a combination of a rhythm generator [central pattern generator (CPG)] and reflexes in response to the peripheral stimulus [1]. The CPG is defined as a neural circuit that can produce self-sustained patterns of behavior [2], and implementation of artificial CPG is usually achieved under the form, either of artificial neural networks [3], or of nonlinear oscillators [4].

In some past studies [5-7], all joints are controlled by the output of oscillators; the dimension of CPG is high, and many parameters have to be determined. Therefore, combing CPG-based method and passivity of the robot would be attractive not only for more robust locomotion but also for control of various types of robots.

In this paper, we present highlights of results in our development of a direct, efficient and robust control strategy by combining CPG-based method, reflex controllers and passive dynamics for a kneed biped robot with semicircular feet. Our goal is to realize blind walking on unknown slope-changed terrains relying purely on sensors and adjustments of posture with no prior experiences: 1) we use a simple periodic function (sinusoid) as the output of CPG only used to actuate the hip joint to swing the leg; 2) we utilize the passive property of biped walking by ceasing the output of CPG after the swing leg is fully extended; as a result the walking is quite efficient; 3) we discover the inherent reasons of falling and propose a measuring function; 4) a falling tendency reflex controller is used to adjust parameters of the output based on initial conditions of a step; 5) a span angle reflex controller is designed to provide a secondary actuation based on parameters of a certain moment to improve the landing performance; 6) controllers cooperate to form a hierarchical control system, which requires no prior knowledge of terrains and no complex learning process. Results of simulations show that the proposed walking strategy meets the requirements of blind walking on unknown slope-changed terrains and has a good robustness.

The rest of this paper is organized as follows. Section II describes the kneed biped model, the sloped terrain model and basic hypotheses for the walking gait. Section III introduces the proposed control strategy, including asset of reflex controllers. Section IV introduces the results and relevant analysis. Finally, section V concludes the paper.

II. SYSTEM AND TASK INTRODUCTION

We developed a four-link biped robot to realize the experiments of control strategy consisting of several reflex controllers and the CPG output. A flat-slope-flat terrain model is constructed as the slope-changed surface providing perturbations to the walking robot. Finally, we introduce the assumptions of the walking strategy to explain the reflex control system. Details on each part are given below in the remainder of this section.

A. Biped Model

As shown in Fig. 1, the four-link biped robot considered in this paper consists of two legs connected at the hip joint. Each leg is composed of a thigh and a shank connected at a knee joint, which has a kneecap mechanism to prevent the leg from inverting. Both legs have arc-shaped feet that are rigidly attached to the shank, and the center of the arc is located on

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the shank. Two touch sensors are placed on the foot and the kneecap respectively in each leg. These sensors are used to synchronize the biped controller with the robot dynamics. The purpose of this study is to develop a simple, but efficient and robust locomotion strategy by active control only through the hip actuator.

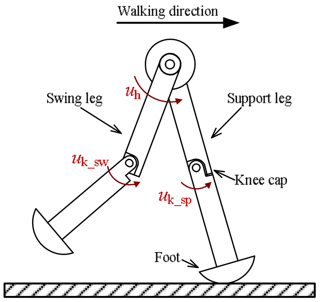


Fig. 1. Schematic of the biped mechanism

The hypotheses assumed for the desired walking gait is now enumerated:

1) Walking consists of a single support phase and an instantaneous double support phase. [8]
2) The support leg is always straight during walking.
3) The swing leg is fully extended before foot contact.
4) The contact of the swing shank with the knee cap is assumed to be a completely inelastic collision.
5) The contact of the swing leg with the ground is also assumed to be a completely inelastic collision. [8]

Under above hypotheses, the single support phase can be divided into two phases from an aspect of the difference of the basic equation. As shown in Fig. 2, *the first phase* is from the start of the swing leg motion to collision at the knee; *the second phase* is from the knee collision to the touchdown of the straight swing leg. The similar model and hypotheses were used by Ono *et al*. [9] and Harata *et al*. [10].

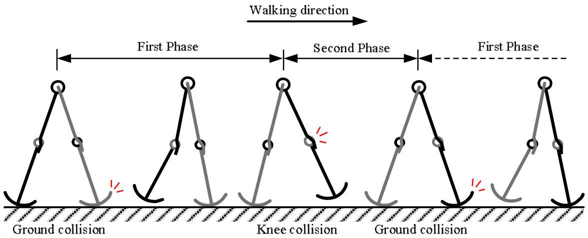
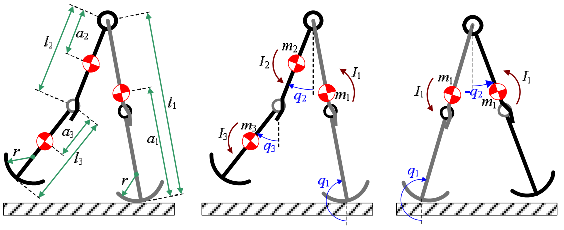


Fig. 2. Phases of biped locomotion

Fig. 3 (a) and (b) shows link parameters of the biped robot, where l_i denotes link length, a_i denotes the position of center of mass, r denotes foot radius, m_i denotes link mass and I_i denotes inertia around mass center. Physical parameters of the robot are shown in [11].



(a) Link parameters (b) Coordinates for phase 1 (c) Coordinates for phase 2

Fig. 3. Link parameters and coordinate definition of the biped robot

B. Sloped Terrain Design

As shown in Fig. 4, the experiment environment is designed as a three-phase terrain. The first and third parts of the terrain are level grounds, and the second part is inclined. The inclined angle α ranges from 0°to 5°. We regard the transitions of phases as perturbations. So through this terrain set, we can observe the performances of robot walking under two kinds of perturbations (level to slope transition and slope to level transition).

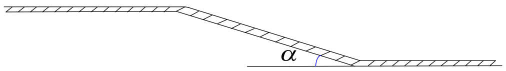


Fig. 4. The constructed model of slope-changed terrain

We construct this terrain under some assumptions below:

1) The first transition is triggered when the walking enters into a stable status on level ground.

2) The second transition is triggered when the robot has successfully walked stably on the sloped surface.

3) The third phase ends when the walking enters into a stable status on level ground again.

4) The transition occurs soon after a certain step finished, then the robot will begin the next step on a new surface tangential to the support round foot with certain angle of dip. This design avoids complex considerations, in order to simplify the transition details and focus our attention on the impacts brought to dynamic systems.

C. Assumptions of the Walking Strategy

The basic assumption for our work on developing reflex controllers is that the realized walking is blind, which means no prior knowledge of the terrain can be depended on, the robot has no experiences gained to learn from. The robot can only “feel” its environment and make quick decisions based on the information from sensors to calculate the environment and evaluate its dynamic conditions. As we can see from Fig. 5, soon after each step finishes the angle of inclination can be calculated as:

$$\alpha = \frac{q_1^+ + q_2^+ - \pi}{2} \tag{1}$$

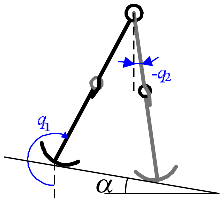


Fig. 5. The posture of robot on inclined surface

Such blind walking strategy enables biped robots walking stably with rapid adjustments on slope-changed terrains with no prior information. However, since blind walking is even really hard for human beings, blind walking for robots can only deal with environment conditions with no drastic change. And that is why we limit the inclined angle α in the range from 0°to 5°

III. REFLEX CONTROL SYSTEM DESIGN

We select several feedbacks to analyze the reasons of falling. Detailed factors contributing to falling forward and backward are discovered. Further, we propose a falling tendency detection expression. Hierarchical controllers are designed to determine the control parameters of certain step and improve landing performances based on feedback information at the beginning of a step and when the support leg is vertical to the level ground. Controllers of different levels cooperate to form up the whole reflex control system. Details are introduced below.

A. Feedbacks and Reason of Falling

1) Feedback Parameters

We pick out several feedbacks as key parameters to determine the dynamic conditions of the robot walking:

q_1, q_2, q_3 represent respectively the angular situations of support leg and swing leg; $\dot{q}_1$ represents the dynamic situation of support leg and can be regarded as a partial signal of dynamic situation of the whole robot system.

Let q^-, q^+, $\dot{q}^-$, and $\dot{q}^+$ denote the pre- and post-impact generalized positions and generalized velocities, respectively.

The superscript "–" and "+" will denote quantities immediately before and after impact thereinafter. Feedbacks after the impact are used to evaluate the environment such as the angle of inclination can be calculated as shown in (1).

We mainly analyze feedbacks after impact since they determine the upcoming step conditions.

2) Reason of Falling Forwards

In our simulation model, falling forwards means that ground impact comes before knee impact. In other words, the robot leans forward so fast that its swing foot touches the ground without its swing leg being fully extended. Since there is no actuation on the swing knee joint before knee collision, the robot will inevitable fall, as shown in Fig. 6 (a).

Through analysis of feedback parameters above, we propose that two factors contribute to falling forwards; 1) The value of $\dot{q}_1^+$, which signifies the forward velocity of robot is overly large. 2) The value of q_1^+, which signifies the span of two legs at the beginning of this step is overly large.

Aiming at these two factors, we put forward the adjusting strategy correspondently. These two factors describe the situation that a person is suddenly tripped by a stone when he is walking stably without anticipating that. In our life experiences, we tend to instinctively take a long and quick step; first swing the thigh rapidly to drive the shank to swing, and then retrieve the thigh to make sure the leg extend fully and land steadily. So we designed a controller to first increase the hip torque to drive the thigh and then output a negative torque to retrieve the swing leg. Detailed adjusting strategy in simulation will be introduced in the controller part.

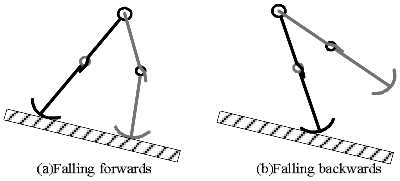

(a)Falling forwards (b)Falling backwards

Fig. 6. Falling forwards and backwards postures

3) Reason of Falling Backwards

Falling backward means the swing leg does not touch the ground normally. The swing leg swings back and touch the ground when $q_1^- < \pi + \alpha$, which means the robot has not entered into the next step, as shown in Fig. 6 (b).

We propose that leaning back falling is triggered by two factors; 1) The value of $\dot{q}_1^+$ is too small. 2) The value of q_1^+, is too small. The underlying reason of this phenomenon is the lack of kinetic energy. The remaining kinetic energy after ground impact is not enough to compensate the gravitational energy, which makes the mass center fail to move past the standpoint in time.

Facing with this situation, a person will instinctively swing the leg out first and then hold for a while waiting for the mass center to move past the standpoint. Consequently, in our designed strategy, after the leg is swung out by the output of CPG controller, a secondary actuation will be provided by auxiliary controllers to hold the leg for a while. Details will also be introduced in the following controller part.

B. Controller Design

Based on proposals analyzed above, a hierarchical reflex control system (HRCS) is designed to achieve blind walking on slope-changed terrains. A CPG controller outputting sinusoidal actuation is used as base controller. A higher level main controller is designed to adjust parameter of CPG controller to deal with leaning forward or backward tendencies. Moreover, we design an auxiliary controller to improve the landing performance by adding a secondary actuation with constant value.

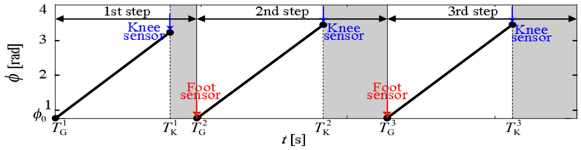
1) CPG Base Controller

We design the hip torque u_{h} driven by the output of CPG as below. One of the simplest ways to design the rhythm signal of CPG is based on a sinusoidal function of amplitude A and phase ϕ and bias parameter B by

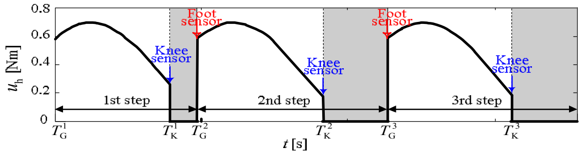
$$u_{\mathrm{h}}(t) = \begin{cases} A \cdot \sin\phi + B, & T_{\mathrm{G}}^{i} < t \le T_{\mathrm{K}}^{i} \\ 0, & T_{\mathrm{K}}^{i} < t \le T_{\mathrm{G}}^{i+1} \end{cases} \qquad (2)$$

Where $\phi = \omega \cdot (t - T_{\mathrm{G}}^{i}) + \phi_0$, T_{G}^{i} and T_{K}^{i} are time instants of ground collision and knee collision in the i-th step respectively, and ϕ_0 is the initial phase of the oscillator.

The CPG is modulated by sensory inputs as shown in Fig. 7. The knee impact signal and ground impact signal acquired from touch sensors cooperate to control the start/cease status of the oscillator on the hip joint. This intermittent control was inspired by the studies on the measurement of human electromyographic (EMG) [12] and the idea of Quasi-PDW conducted by Collins *et al.* [13]



(a) Phase



(b) Output of the sinusoidal intermittent oscillator

Fig. 7. Modulation of the intermittent oscillator due to feedback signals from foot sensor and knee sensor.

For the above design, the numbers of CPG parameters are smaller than that used in the existing neural oscillator approach. And amplitude A is the parameter we adjust in the following main controller.

2) *Falling Tendency Controller*

As discussed above, we proposed that $\dot{q}_1^+$ and q_1^+ are two influential factors relevant to falling tendency. Based on this proposal, we put forward the falling tendency expression:

$$K_{tend} = k_{position} \times (q_1^+ - \pi) + k_{velocity} \times \dot{q}_1^+ + k_{slope} \times \alpha + C_{bias} \quad (3)$$

where α represents the slope of current ground, which means if the robot steps on level ground, the value of α is 0. When $K_{tend} > 0$, the robot walking has the tendency of falling forwards. When $K_{tend} < 0$, the robot walking has the tendency of leaning backward. K_{tend} is updated at the beginning of each step, so that control strategy can change correspondently.

Based on expression (3), the main controller is developed to ensure stable walking on unknown terrains. The controller is triggered at the beginning of each step. Amplitude A_{out} is the adjusted parameter and output of this controller:

$$A_{out} = A_{slope} + A_{rect} \quad (4)$$

where A_{slope} is a basic value considering influence of slope, it only predicts a proper amplitude for each slope angle as:

$$A_{slope} = A_{level} + k_{Aslope} \times \alpha \quad (5)$$

and A_{rect} is a control variable providing rectification against falling tendencies. For example, if K_{tend} is positive, we set $A_{rect} > 0$ to increase the hip torque. We define A_{rect} as:

$$\begin{aligned} A_{rect} &= C_{Amp} \times (k_{position} \times (q_1^+ - \pi) + k_{velocity} \times \dot{q}_1^+ + k_{slope} \times \alpha + C_{bias})^3 \\ &= C_{Amp} \times K_{tend}{}^3 \end{aligned} \quad (6)$$

We use the third power of K_{tend} intending to: 1) reduce the value of A_{rect} when the falling tendency is slight to avoid drastic oscillation; 2) increase the value of A_{rect} sharply when the falling tendency is obvious. The controller is to design a dynamic well to trap walking conditions in a limit cycle.

To determine values of control parameters, especially for A_{level} and k_{Aslope}, we run simulations under various slope conditions and amplitudes of actuation. Further, we extract $\dot{q}_1^+$ and q_1^+ together with α in each situation to analyze falling tendencies and control strategy. We use ample specific walking moments as sample calibrations. By substituting these conditions into equations (3)-(6), we determine approximate value of parameters as solutions of equations. Then we use these parameters to test our control theory and gradually adjust them into precise values shown in Table I.

TABLE I
CONTROL PARAMETER VALUES FOR FALLING TENDENCY CONTROLLER

Lable	$k_{position}$	$k_{velocity}$	k_{slope}	k_{Aslope}	A_{level}	C_{bias}	C_{Amp}
Value	4.5	0.52	0.01	0.15	0.7	0.126	5

3) *Span Angle Controller*

In order to improve the landing performance, we design the span angle controller, since the falling tendency controller makes decisions only based on initial conditions of a certain step and its output influences the earlier part of the step. The span angle controller acquires feedback information when the support leg is exactly vertical to the level ground. Then the controller predicts the landing condition and outputs correspondently a secondary actuation replacing the sinusoidal torque. The secondary actuation is a constant torque with the value of A_{2nd}. It begins when phase ϕ of the sinusoidal torque reaches π and ends with ground impact. The value of A_{2nd} is determined following rules below:

$$A_{2nd} = \begin{cases} A_a & q_3 - q_2 > 4 \times \alpha + 0.175 \quad (a) \\ A_b & q_1 - q_2 - \pi < -\alpha \quad (b) \\ A_c & \dot{q}_1 < 0 \quad (c) \\ A_d & emergency = 1 \quad (d) \\ 0 & otherwise \quad (e) \end{cases} \quad (7)$$

For condition (a) and (b), we set the A_{2nd} to be negative to retrieve the swing leg in order to avoid falling forwards. For condition (c), A_{2nd} is positive in order to avoid falling backwards by holding the swing leg for a while waiting for the mass center to move past the standpoint. It can also improve the landing by enlarging the span angle in this step and further reduce the risk of leaning forward in the next step. Condition (d) is special: at the beginning of each step, the controller will consider robot to have serious potential of falling backwards if $q_1^+ - q_2^+ - \pi < -0.465 - 0.047 \times \alpha$ and set signal “emergency” to be 1, to provide a large enough hold torque against gravity, which makes the leg swing back so quickly that the mass center has not moved yet. Condition (e) shows the robot is walking safely with no need of landing improvement.

The criterions through (a) to (e) cover all important information for robot at that moment. These criterions are speculated from adequate simulations and analysis of results. Moreover, we take the same method to determine values of A_{2nd} in each condition as used in falling tendency controller.

TABLE II
CONTROL PARAMETER VALUES FOR SPAN ANGLE CONTROLLER

Lable	A_a	A_b	A_c	A_d
Value	-0.5	-2	1.77	4

IV. RESULTS AND ANALYSIS

This section highlights our simulation results for the combination of three controllers described in Section III. Summarized briefly, the CPG controller is effective in providing sinusoidal actuation according to feedback signals from foot sensor and knee sensor. The falling tendency controller is effective in adjusting the amplitude A properly according to different slopes and falling tendencies with A_{rect}. The span angle controller acts as an auxiliary controller to deal with landing problems and some extreme or emergent situation when robot needs a large enough hold torque.

A. Performance of CPG controller

We constructed biped robot model in the simulation environment of Mathworks MATLAB/Simulink R2007b. Fig. 8 illustrates the change of angular position q_1 and velocity $\dot{q}_1$ of support leg in the phase plane with the parameters $A = 0.4$ [Nm], $B = 0.3$ [Nm], $\omega = 2\pi$ and $\varphi_0 = \pi / 4$. The gaps in the phase plane diagram are due to the collisions at the knee and the ground. A stable limit cycle is generated by the proposed method. It also should be noted that, for different initial conditions with same control parameters, same stable limit cycle is obtained. It indicates that the stable limit cycle is unique for particular control parameters.

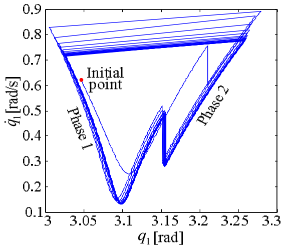


Fig. 8. Phase plane illustration of the support leg

In this paper we set $B = 0.2$ [Nm], $\omega = 2\pi$ and $\varphi_0 = \pi / 4$. If we set $A = 0.7$ [Nm] without adjustments through reflex controllers, the robot can walk steadily on the level ground. However, it will fall down on the designed slope with $\alpha = 2.5°$. Angular conditions and stick figures are demonstrated in Fig.9 and Fig.10.

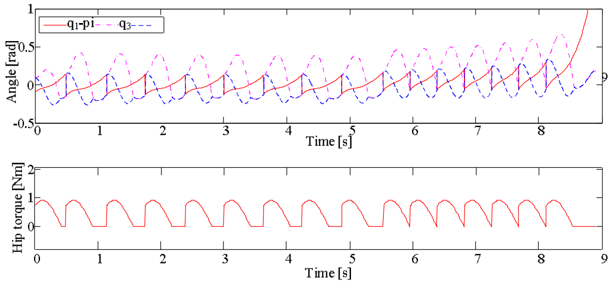


Fig. 9 Angular conditions and torque map of walking with no reflex control

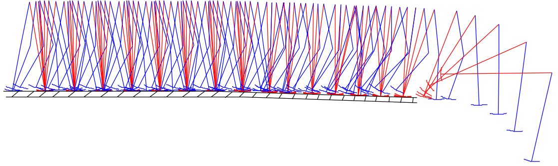


Fig. 10 Stick figures of walking patterns with no reflex control

B. Performance of Falling Tendency controller

It is hoped that the falling tendency controller can produce stable results against falling tendencies to maintain the walking conditions in a limit cycle. Results of simulations show that the designed controller combined with CPG produce satisfying robustness against perturbations brought by the change of slope. It is especially effective towards moments when the terrain change from level ground to inclined surface. However, because of the lack of actuation on knee joints and ankle joints, inherent fragility of four-link passive walking easily leads to oscillation and bring extreme conditions, most of which are falling back problems. Moreover, feedback information acquired at the initial moment of a step cannot represent the walking conditions of whole step. Sinusoidal actuation alone without compensatory actuation fails to meet demand of a flexible control strategy.

C. Performance of Reflex Control System

Our most impressive performance by far is obtained by combining the base CPG controller, the high level falling tendency controller with the auxiliary span angle controller. The optimal control policy converges to a successful policy for continuous and stable walking on the terrain with slope angle ranging from 0 ° to 5 °. Primary adjustments in amplitude A cope with the perturbations of slope changing. Secondary actuations improve the landing performance and the initial conditions for the next step.

With the combination of three controllers above, the reflex control system is formed, and the torque map of a healthy walking when $\alpha = 5°$ is shown as Fig. 11.

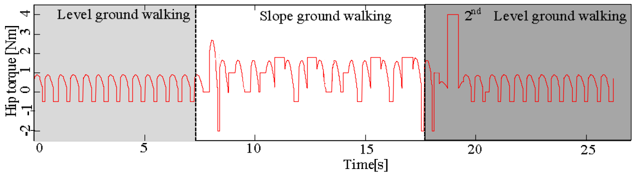


Fig. 11. The torque map outputted by the reflex control system.

Fig.12 shows the change of angular position q_1 and velocity $\dot{q}_1$ of the support leg in the phase plane of successful walking when slope angle is 5 °. Small cycle shows stable walking on level ground; big cycle shows walking with adjustments on inclined surface. Fig. 13 shows angular displacement during walking. After disturbance, the walking gait soon returns to a new stable orbit. This demonstrates that the walking gait is robust against environment variation. Changes of span angle of initial condition are described in Fig.14. Fig.15. shows the corresponding stick figures of controlled walking on 5 ° slope-changed terrain.

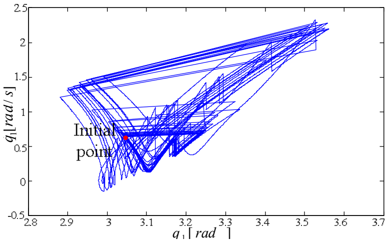


Fig. 12. Phase plane illustration of the support leg

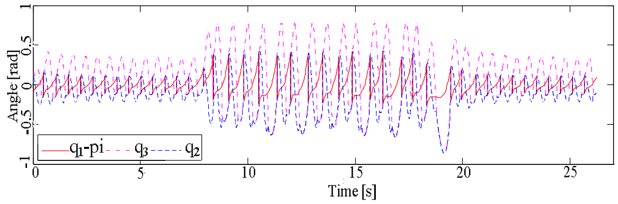


Fig. 13. Angular conditions of all the joints

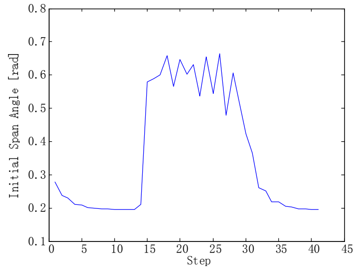


Fig. 14. Span angle changes

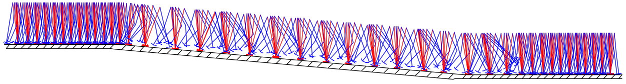


Fig. 15. Stick figures of walking patterns on slope-changed terrain

V. CONCLUSIONS AND FUTURE WORK

In this study, based on a four link walking robot with knees and feet, a direct and efficient walking strategy is presented by combination of central pattern generation and reflex controllers. Three hierarchical controllers cooperate synthesizing a reflex control system. The system simulates the whole walking process of human: CPG controller stands for primary habitual walking; falling tendency controller represents human ability to adjust towards various walking conditions; span angle controller simulates the instinct of rapid reflex towards extreme or emergent situations. It is shown that biologically plausible walking dynamics can be achieved by using reflex controllers without learning period. The results of this paper are summarized as follows.

1) We discover the intrinsic reason of falling, and propose corresponding measures stabilize the walking based on actual life experiences of human being. An expression inspecting falling tendencies is put forward and proved plausible.

2) The output of CPG is simply based on a sine oscillator. Combined with passive property of biped walking, the CPG controller has few parameters to be controlled. And the walking pattern is quite efficient, and seems to be comparable with human beings.

3) Falling tendency controller is designed to determine the main control policy based on initial conditions. Span angle controller is acting an auxiliary role improving landing performance, providing better initial conditions for next step and solving emergent and serious walking problems.

4) The proposed walking method is robust to perturbations caused by slope change. Continuous and stable walking can be achieved with no prior knowledge of the terrain and no foresight of the slope change. No learning process is needed since the control strategy is designed based on intrinsic dynamic principles.

The effectiveness of our walking strategy derives from the combination of self-stabilizing properties of biped locomotion and reflex control against falling tendencies. We believe that this strategy is plausible in the perspective of understanding of human walking with instinctive adjustments. In the future, we will consider using more optimization methods to acquire precise parameters of each controller in order to increase the robustness of walking on bumpy ground. We will also enrich the terrain library. In addition, we will conduct experiments with a prototyping biped robot.

APPENDIX

This paper has supplementary downloadable material.

TABLE III
ELECTRONIC ANNEXES

Annexes	Type	Description
1	Video	Successful walking with two slope changes
URL	http://learn.tsinghua.edu.cn:8080/2006010583/1.avi	
2	Video	Stable walking on long slope
URL	http://learn.tsinghua.edu.cn:8080/2006010583/2.avi	

REFERENCES

[1] V. Dietz, "Spinal cord pattern generators for locomotion," *Clinical Neurophysiology* 114, 1379-1389, 2003.
[2] S. Grillner, "Neurobiological bases of rhythmic motor acts in vertebrates," *Science* 228, 143-149, 1985.
[3] K. Matsuoka, "Sustained oscillations generated by mutually inhibiting neurons with adaption," *Biological Cybernetics* 52(6), 367-376, 1985.
[4] L. Righetti and A.J. Ijspeert, "Programmable central pattern generators: An application to biped locomotion control," *2006 IEEE Conference on Robotics Automation*, pp. 1585-1590.
[5] G. Taga, Y. Yamaguchi, H. Shimizu, "Self-organized control in bipedal locomotion by neural oscillators in unpredictable environment," *Biological Cybernetics* 65, 147-159, 1991.
[6] Y. Fukuoka, T. Mimura, N. Yasuda, H. Kimura, "Integration of multisensors for adaptive walking of a quadruped robot," *2003 IEEE Conference on Multisensor Fusion and Integrated Intelligent Systems*, pp. 21-26.
[7] S. Aoi, K. Tsuchiya, "Stability analysis of a simple walking model driven by an oscillator with a phase reset using sensory feedback, " *IEEE Transaction on Robotics* 22(2), 391-397, 2006.
[8] E.R. Westervelt, J.W. Grizzle and D.E. Koditschek, "Hybrid zero dynamics of planar biped walkers," *IEEE Transactions on Automatic Control* 48(1), 42-56, 2003.
[9] K. Ono, T. Furuichi and R. Takahashi, "Self-excited walking of a biped mechanism with feet," *The International Journal of Robotics and Research* 23(1), 55-68, 2004.
[10] Y. Harata, F. Asano, Z. Luo, K. Taji and Y. Uno. "Biped gait generation based on parametric excitation by knee-joint actuation," *Robotica*, Vol. 27, 2009.
[11] C. Fu, F. Tan and K. Chen, "A simple walking strategy for biped walking based on an intermittent sinusoidal oscillator," Robotica, 2010, to be published
[12] C. Capaday, "The special nature of human walking and its neural control," *Trends in Neurosciences* 25(7), 370-376, 2002.
[13] S.H. Collins, A. Ruina, R.L. Tedrake and M. Wisse, "Efficient bipedal robots based on passive-dynamic walkers," *Science* 307, 1082-1085, 2005.