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CPG-Based Control Design for Bipedal Walking on Unknown Slope Surfaces

Kai-Tai Song, *Member, IEEE,* and Chang-Hung Hsieh

Abstract—**The paper presents a walking pattern generator and a balance control system for a bipedal robot to handle an unknown slope. The robot uses onboard gyro and accelerometer sensors to detect the pose information of the upper-body. A controller is proposed for the robot to walk on an unknown slope by adjusting the tilt angle of the upper-body. The theory of central pattern generator (CPG) is applied to generate the walking trajectory. By using the pose information of the upper-body, we developed a method to determine the relationship between the slope surface and the upper-body pose and generate the compensation motion to adjust the tilt angle of the upper-body. The compensation control consists of predictive compensation and immediate compensation. The predictive compensation responds to adjust the upper-body pose before beginning of the next step. The immediate compensation is applied to adjust the upper-body pose during the single support phase. The integrated controller adapts to the unknown slope in real time while robot walking. Using the bipedal robot NAO, the experimental results show that the biped robot can walk successfully on unknown slopes.**

I. Introduction

Humanoid robotics has made remarkable progress in recent years. Various biped robots have been developed for contests, entertainment, and research purposes because of their friendly appearance and capacity of mobility. However, for robots to step down from the performing stage and start to walk in daily-life human environments, balance control will pose a challenging problem. Many useful tools have been developed to allow biped robots to walk stably on a flat surface. They are basically offline walking gait generating schemes and pre-designed ideal walking trajectory using a stable criterion. Bipedal walking on unknown terrains is much more complicated and one of the most important research topics in bipedal robotics. There are increasing interests that attempts to design compensation control schemes to online adjust the walking trajectory in order to satisfy the stable strategy by sensory information to achieve balance walking on unknown surfaces [1][2].

The study of biological walking based on neural periodic control of locomotion has drawn increasing attention in recent years [3][4]. Central Pattern Generators (CPGs) are networks of nonlinear oscillation neurons found in both invertebrate and vertebrate animals that can produce rhythmic patterns of neural activity without receiving rhythmic inputs from higher control centers. Many attempts have shown that CPG can be used as the main controller for balance walking of biped and multi-legged robots on irregular terrains [5-11]. The study of CPG-based bipedal walking has focused on developing different walking pattern to achieve balance walking on flat surfaces [12-15]. Accordingly, we consider that to employ CPG method as the main controller for bipedal balance walking on irregular terrain is more difficult. It is also understood that adjusting the CPG parameters to achieve balance walking is quite complex. In order to increase the degrees of terrain irregularity which bipedal can cope with, we suggest to employ additional methods of reflex and adjustment to cover the limits posed by CPG method. Hence, we will suggest to use multiple CPGs to reduce the complexity of tuning CPG parameters, and to add external control units with the main controller of CPG to achieve balance walking on irregular terrain in the real world.

In this paper, we adopt biological concept of self-produced periodic cycles to design the biped walking pattern. A novel design for pose control of upper-body, based-on two compensation controllers to adjust the pose of upper-body at different phases of walking period. Based on the pose control of upper-body, a bipedal robot can adjust the pose of upper-body to adapt to unknown slope surfaces in real time.

The rest of this paper is organized as follows. In Section II, CPG-based walking pattern generating is discussed. A design for the compensation controller is described in Section III. The experimental results are shown in Section IV. In Section V, we will conclude the contribution of this paper.

II. CPG-Based Walking Pattern Generotion

A walking pattern generator for a biped robot (NAO, in this work) has been designed based on an arrangement of multiple CPGs. We also added an external compensation controller in order to achieve balanced static walking.

A. Neural Oscillator Model

The neural oscillator model proposed by Matsuoka [16-17] was adopted in this work. The Matsuoka oscillator model consists of two neurons arranged in mutual inhibition. The mathematical model among two neurons with adaptation is expressed in continuous-variable form by following equations[16-17]:

Kai-Tai Song and Chang-Hung Hsieh are with the Institute of Electrical Control Engineering, National Chiao Tung University, Hsinchu, Taiwan (phone: +886-3-5731865; fax: +886-3-5715998; e-mail: ktsong@ mail.nctu.edu.tw; poloqe8484.ece99g@nctu.edu.tw). This work was supported by the National Science Council of Taiwan, under grant NSC-99-2221-E-009-135-MY2.

$$\tau_1 \dot{u}_1 = c - u_1 - \beta v_1 - \gamma [u_2]^+ + \sum h_j [g_j]^+ \ , \qquad (1)$$

$$\tau_2 \dot{v}_1 = [u_1]^+ - v_1 \ , \qquad (2)$$

$$\tau_1 \dot{u}_2 = c - u_2 - \beta v_2 - \gamma [u_1]^+ - \sum h_j [g_j]^- \ , \qquad (3)$$

$$\tau_2 \dot{v}_2 = [u_2]^+ - v_2 \ , \qquad (4)$$

$$q = [u_1]^+ - [u_2]^+ \ , \qquad (5)$$

$$[x]^+ \stackrel{\text{def}}{=} max(0, x), \qquad [x]^- \stackrel{\text{def}}{=} min(0, x) \ , \qquad (6)$$

where u_1, u_2, v_1 and v_2 are internal states, γ and β are constants, g_j is an input, h_j is scaled gain, and q is an output of the oscillator. Time constants τ_1 and τ_2 characterize the output wave shape and its frequency and a tonic excitation c modulates the output amplitude.

B. Single Support Phase(SSP)

The motion of striding is a symmetric cycle of periodicity between left and right foot in SSP, so we arrange CPGs to achieve swing foot forward moving and upper-body swing.

In the literatures, an oscillator is allocated at each joint or motor for applying CPGs to locomotion of biped robot[12-13]. Self-coordination is designed between multiple oscillators to obtain the ideal walking gait, but adjusting these parameters is complicated. The computation time would be an issue for practical implementation, considering the feedback control and adjusting the balance of robot using real-time sensory information. Therefore, we want to use fewer oscillators to build the walking pattern, and the parameters of CPGs are adjusted in a simpler way to obtain the output curve of CPGs.

We must let each CPG have different functionality and through the CPG arrangement to produce an integral walking stride. Endo *et al*. proposed some configurations about the arrangement of CPGs [14-15]. With the idea, we allocated four neural oscillators to control the motion of robot in SSP, as shown in Fig. 1. We designed two oscillators which are used to obtain the Cartesian coordinate positions of two feet and waist to produce overall stride curve. The first oscillator is allocated to control the position of both legs p_{Lz}, p_{Rz} along the Z (vertical) direction in a symmetrical manner:

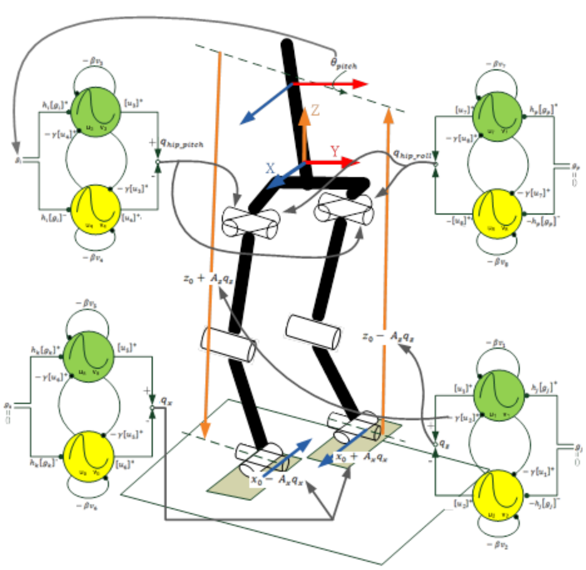


Figure 1. Arrangement of four CPGs for bipedal walking

$$p_{Lz} = z_0 - A_z q_z \ , \qquad (7)$$

$$p_{Rz} = z_0 + A_z q_z \ , \qquad (8)$$

where p_{Lz} is the Z-direction length from left foot to shoulder, p_{Rz} is the Z-direction length from right foot to shoulder, q_z is the output of the oscillator for Z-direction, A_z is the scaled factor of the amplitude of q_z and z_0 is the initial length of Z-direction.

The second oscillator is allocated to control the position of both leg p_{Lx}, p_{Rx} along the X (forward) direction:

$$p_{Lx} = x_0 - A_x q_x \ , \qquad (9)$$

$$p_{Rx} = x_0 + A_x q_x \ , \qquad (10)$$

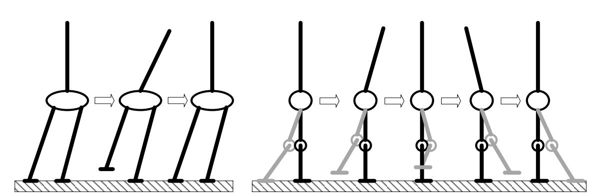
where x_0 is the offset of X-direction between two foot sole in the DSP, p_{Lx} is the difference value between x_0 and the left toot position, p_{Rx} is the difference value between x_0 and the right foot position, q_x is output of oscillator for X-direction and A_x is scaled factor.

Based on the walking strategy for a bipedal with a torso of large mass [18], we consider the center or gravity(CoG) of the robot would change when the swing foot is lifting from the floor. Hence, we need to add the upper-body swing to let the CoG of the robot maintain on a stable region. The upper-body is upright in double support phase(DSP). During the SSP, the upper-body is inclined to the direction of the support foot with the lifting of the swing foot, and then the upper-body is recovered to upright with the landing of the swing foot, as shown in Fig. 2(a). During the SSP, the upper-body is inclined forward with lifting of the swing foot, and then the upper-body is inclined backward with landing of the swing foot, as shown in Fig. 2(b). According to the above strategy, the remaining two oscillators are used to make upper-body of the robot to left-right and forward-backward sway with the stride behavior that produce center of gravity moving to control the robot can maintain balance. Therefore, the third oscillator is allocated to control the pitch joint angle of hip:

$$\theta_{HipPitch\_Swing} = k_{hip\_pitch} \times q_{hip\_pitch} \ , \qquad (11)$$

where $\theta_{HipPitch\_Swing}$ controls upper-body to swing forward-backward, q_{hip_pitch} is oscillator output for pitch plane and k_{hip_pitch} is scaled factor of q_{hip_pitch}. The fourth oscillator is allocated to control the roll joint angle of hip:

$$\theta_{HipRoll\_Swing} = k_{hip\_roll} \times q_{hip\_roll} \ , \qquad (12)$$



(a) Frontal Plane (b) Lateral Plane

Figure 2. The schematics of the upper-body swing

where $\theta_{HipRoll\_Swing}$ controls upper-body to swing left and right, q_{hip_roll} is the oscillator output for roll plane and k_{hip_roll} is the scaled factor of q_{hip_roll}.

For bipedal walking, it is necessary to maintain stable stride by using four oscillators in SSP. The frequency of controlling hip-pitch of CPG is double of the frequency of other CPGs, so that the upper-body can finish swing of an entire period in lateral plane when walking one step(half period of other CPGs).

C. Double Support Phase(DSP)

In the current design, the bipedal walking is static walking and the CoG of upper-body cannot be shifted to a stable position from hind to forefoot by the inertia force in the instantaneous conversion between two SSPs. Therefore, we designed a simple trajectory to control the CoG of upper-body motion in DSP. The upper-body moves from hind to forefoot in Y-direction such that:

$$p_{Sy} = 2(p_{Fy} - p_{Hy})t_S + p_{Hy},\ 0 \le t_S \le T_{Two\_Support}\ , \quad (13)$$

where p_{Sy} is the coordinate of shoulder center in Y-direction, p_{Fy} is the coordinate of forefoot, p_{Hy} is coordinate position of hind foot, $T_{Two\_Support}$ is total time of DSP and t_S is current time in DSP. The purpose is to let the upper body move smoothly from hind to forefoot. The upper-body moves from hind to forefoot in X-direction such that:

$$p_{Sx} = k_{Sx}(1 - exp^{-\frac{t_S}{k_T}}),\ 0 \le t_S \le T_{Two\_Support}\ , \quad (14)$$

where p_{Sx} is the coordinate of shoulder center in X-direction, k_{Sx} is scaled gain of shoulder center moving in X-direction, k_T adjusts the curve of shoulder center moving in X-direction. The purpose of the formula is to allow the upper body to move slowly in the X-direction after the center of gravity switching from hind to forefoot, so that the sensing information obtained by the sensors can be more accurate.

III. The Compensation Design of Balanced Walking

As far as walking on slope surfaces is concerned, human can achieve balanced walking through adjusting the pose of upper-body. Moreover, when human walk on unknown slope surface with closed-eye, he/she is able to preliminary adjust the pose of upper-body by sensing of the underneath surface which located on the forefoot in the latter half of DSP. Further, if we feel unbalanced in SSP, we will immediate adjust the pose of upper-body to recovery balance. From the concept of human walking, we suggest to build the overall system of bipedal walking, as shown in Fig. 3.

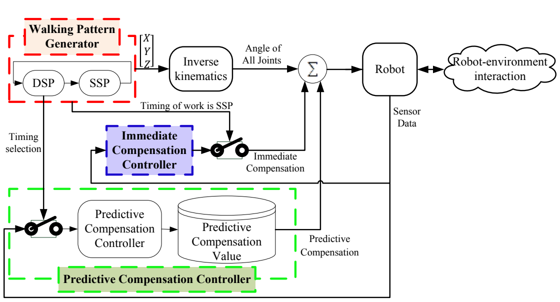


Figure 3. Overall system architecture of bipedal balance control

Because the walking pattern only allows the biped robot to walk on flat surfaces, we must use the sensory data from onboard the robot to control the pose of upper body to achieve balanced walking on unknown slopes. As shown in Fig. 3, the strategy of controlling the pose of upper body is divided into two parts to achieve balance control, namely, the predictive and immediate compensation controllers. They are suggested to satisfy the balance walking strategy.

A. Design of Predictive Compensation Controller

Before the start of SSP of the next step, we hope the robot can accomplish the predictive compensation control so that the robot can successful adapt to the varying slope to prevent fall in the next walking step. Hence, the predictive compensation value must be calculated in the timing of latter half of DSP. The timing of latter half of DSP represents the meaning of completing to move the CoG from hind foot to forefoot. The predictive compensation controller is designed to calculate the predictive compensation value in DSP, but the value is applied to the next step including the DSP. The trajectory of CoG is obtained through the inverse kinematics of the robot to convert to the ideal angle of each joint, and the ideal angle of each freedom make the bipedal walking. At the same time, the trajectory of CoG provides the timing selection to control the predictive compensation controller to update the predictive compensation value for the variation of the slope surface. First, the sensing information AngY is exploited to estimate the upper-body pose. The angular value and the angular velocity of pitching angle of upper-body are calculated at *k* instant:

$$AngY_{DSP}[k] = (AngY[k-1] + AngY[k])/2\ , \quad (15)$$

$$\omega\_AngY_{DSP}[k] = \frac{AngY[k] - AngY[k-1]}{(t[k] - t[k-1])}\ , \quad (16)$$

where $[k]$ and $[k-1]$ denote sample instants *k* and *k-1*, and these are the instants when the joint angles are output to control robot in DSP, $AngY$ is sensor data of pitching angle of upper-body, t is timer, $AngY_{DSP}[k]$ is angular value of pitching angle of upper-body at *k* instant and $\omega\_AngY_{DSP}[k]$ is angular velocity value of pitching angle of upper-body at *k* instant.

We want to obtain more accurate angular value of pitch angle of upper-body in DSP, and the following formula is used to calculate it:

$$AngY_{Torso} = k_\theta \times AngY_{DSP} + k_\omega \times \omega\_AngY_{DSP} \times t_c\ , \quad (17)$$

where $AngY_{Torso}$ is the angular value of pitch angle of upper body in DSP, k_θ and k_ω are scaled factors and t_c is the average execution time. The predictive compensation value is exploited to adjust the angle of the Hip-Pitch joint and alter the input of Hip-Pitch CPG to tune the Hip-Pitch CPG curve:

$$\theta_{pitch\_comp01}(S+1) = -AngY_{Torso} + \theta_{HipPitch\_Swing} + \theta_{pitch\_comp01}(S)\ , \quad (18)$$

$$g_i = k_{gi} \times \theta_{pitch\_comp01}\ , \quad (19)$$

where (S) is step, θ_{pitch_comp01} is predictive compensation value for pitch plane, $AngY_{Torso}$ is angular value of pitching angle of upper-body in DSP, g_i is the input of oscillator for pitch plane and k_{gi} is a scaling factor. In DSP, the predictive compensation value will directly feedback to the Hip-Pitch joint so that the pose of upper-body can maintain upright to the flat ground.

B. Design of Immediate Compensation Controller

The predictive compensation controller is used to control the pose of upper-body to cope the variation of slope for the next step. However, during the SSP, the robot itself may encounter disturbance or the foot in contact with the ground may generate steering force/torque to make the robot lose balance. Therefore, real-time pose sensing is used to immediately regulate the attitude angle of upper body, so that the robot can keep balance in SSP. In SSP, using the direct joint control and the walking trajectory can make the robot to achieve balanced striding on flat surface. In order to overcome the disturbance to maintain stable striding, we suggest a design of the immediate compensation controller, which includes immediate compensation on pitch plane and roll plane. The value of pitching angle of immediate compensation is calculated as shown in (20). The method adjusts the upper-body pose to maintain ideal pose.

$$\theta_{pitch\_comp02} = k_{pcp02} \times (AngY - (\theta_{HipPitch\_Swing} + \theta_{pitch\_comp01})) , \quad (20)$$

where θ_{pitch_comp02} is the immediate compensation value for pitch plane and k_{pcp02} is scaling factor.

The value of roll angle of immediate compensation is calculated in (21). The purpose is to make the upper body not to swing to the direction of support leg too much when the swing foot has been lifted.

$$\theta_{roll\_comp} = k_{rcp} \times (-AngX - \theta_{HipRoll\_Swing}), \quad \text{if } |\theta_{HipRoll\_Swing}| < |AngX| , \quad (21)$$

where θ_{roll_comp} is the immediate compensation value for roll plane, k_{rcp} is scaling factor and $AngX$ is the measured rolling angle.

Finally, joint angle integration is designed to sum all control values of each joint. The control values include the swing value of the upper body and the compensation value. The totaled values are allocated to control the joint of Hip-Pitch and the joint of Hip-Roll, as following equation (22)(23).

$$\theta_{HipPitch\_All} = \theta_{HipPitch\_Swing} + \theta_{pitch\_comp01} - \theta_{pitch\_comp02} \quad , (22)$$

$$\theta_{HipRoll\_All} = \theta_{HipRoll\_Swing} - \theta_{roll\_comp} \quad , \quad (23)$$

where $\theta_{HipPitch\_All}$ is the sum of angular value of Hip-Pitch joint and $\theta_{HipRoll\_All}$ is the sum of anglular value of Hip-Roll joint.

The two totaled values will be added to the desired angles of all joints which are calculated by the walking trajectory so that the robot can achieve balanced walking on unknown slope surfaces, even if the robot encounters disturbance situations.

C. Phase Selection of Compensatory Control

The working phase of two controllers is shown in Fig. 4. The predictive compensation controller predicts compensate value when the last two sensing data are sampled during the latter half of DSP. The predict compensation value will be applied in the next walking period. The predict compensation value is maintained in the walking period until the new predict compensation value is calculated. The immediate compensation controller works all the time during the SSP, and the compensate value will immediately update with received sensory information.

IV. EXPERIMENTAL RESULTS

The proposed method has been implemented on the humanoid robot NAO in order to verify the effectiveness of the design. We let the robot walk on four different changing terrains: “Flat→ 4° Uphill→Flat”, “Flat→ 4°Downhill→Flat”, “Flat→ 7°Uphill” and “7°Downhill→Flat”.

For the experiment of robot walking on the terrain of “Flat → 7°Uphill”, the recorded sensory data-AngY and AngX are shown in Fig. 5. In lateral plane, it occurred that the upper-body tilted backward in the beginning of the 7° uphill, then through compensation control, it recovered with the upper-body pose as if the robot is walking on a flat surface, as shown in Fig. 5(a). In frontal plane, the swing of the upper-body was stable and symmetric, but when walked on the rear part of uphill, the robot walked toward right side with a curve-up of AngX, as shown in Fig. 5(b).

The compensate data of predictive compensation controller is shown in Fig. 6. The predictive compensation values of tilt angle of upper-body approximately corresponding to the varying of sloped angles, but the convergence speed was slow when the robot walked from flat to uphill terrain, as shown in Fig. 6(a). The CPG input affects the curve of CPG output to move up when walking on uphill. The upper body tilted forward in DSP, but the condition does not affect balance, as shown in Fig. 6(b)

The compensate data of immediate compensation controller is shown in Fig. 7. In lateral plane, although the convergence speed of predictive compensation control was slow and caused the predictive compensation values to be smaller than the ideal values, the immediate compensation controller remedied the error to make the robot to maintain balance by producing larger negative values in the beginning of walking on 7°uphill, as shown in Fig. 7(a). In frontal plane, the immediate compensation of the right foot is as

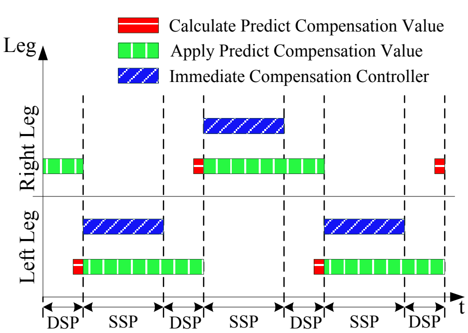
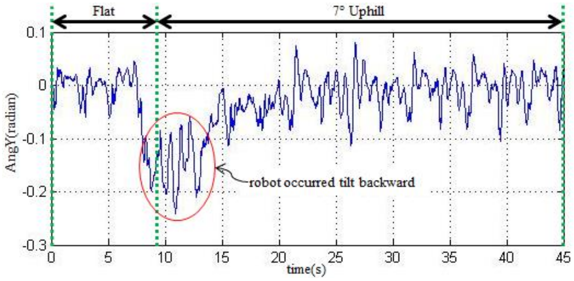
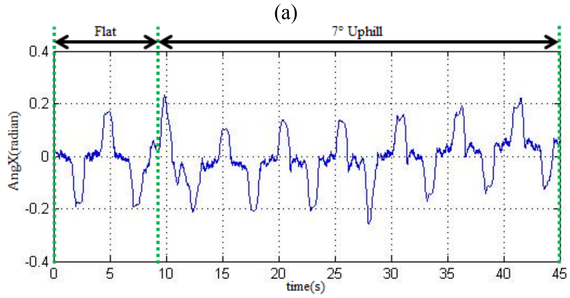


Figure 4. The working phase of two controllers

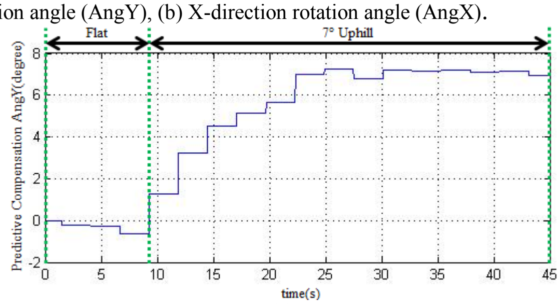


(a)

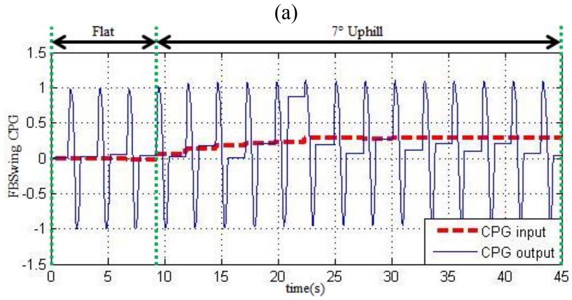


(b)

Figure 5. Recorded sensory data during bipedal walking: (a) Y-direction rotation angle (AngY), (b) X-direction rotation angle (AngX).



(a)

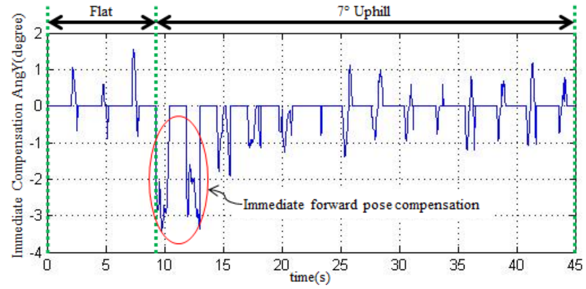


(b)

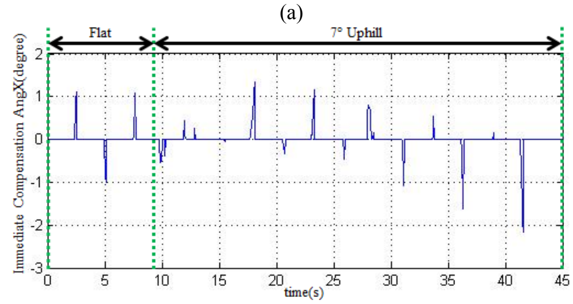
Figure 6. Recorded predict compensation data during bipedal walking: (a) Predictive compensation value on pitch plane, (b) The output of CPG is to control the upper-body swing in front-rear direction.

support foot is larger than the value of left foot is as support foot on rear section of uphill (positive values are larger than negative values), in order to let the robot cannot fall to the direction of right, as shown in Fig. 7(b).

We calculated and recorded the ZMP of the robot in the experiments to verify the stability of NAO when walking from flat to 7° Uphill. The recorded ZMP trajectories are shown in Fig. 8. In Fig. 8, the stable regions of ZMP are depicted by the solid red line. It can be seen that the robot kept walking stably on 7° Uphill using the proposed controller. However, without control the robot fell and the ZMP moved out of the sable region in SSP at the start 7° Uphill. The recorded sensory data are shown in Fig. 9. In Fig. 9, we see that without control the robot fell to the right side, because of the upper body of robot rotated too much to



(a)



(b)

Figure 7. Recorded immediate compensation data during bipedal walking: (a) Immediate compensation value on pitch plane, (b) Immediate compensation value on roll plane.

right and caused the ZMP trajectory to move outside the stable region of the left foot in SSP. Furthermore, we see in Fig. 8(b) and Fig. 9(a) that without control the robot fell backward, because of the upper body of robot tilted backward too much to cause the ZMP trajectory to move outside the stable region. On the contrary, the ZMP trajectories are in the stable region for the robot walking on the same slope with the proposed compensation controller.

From the above experiments, we verified that the predictive compensation controller can make the robot to obtain initially stability when encounter a sloped surface. The predictive compensation values are accurate and they converge to within 2°. Although the convergence speed of predictive compensation is still slow, the immediate compensation controller provides the fast immediate correction to allow the robot to maintain balance. Furthermore, the immediate compensation controller can maintain the swing amplitude in Y-direction of the upper-body to allow the robot not to be affect by the inertia force of CoG in the Y-direction. Hence, we consider the predictive compensation controller and the immediate compensation controller are effective to let the robot maintain walking balance on unknown slope surfaces.

V. CONCLUSION

In this work, a walking pattern is generated to combine multiple CPGs in SSP and the trajectory motion of CoG of the upper body in DSP to achieve stable static walking. We have developed a method to determine the relationship of the slope of terrain and the upper-body pose, in order to generate the predictive compensation to adjust the tilt angle of the upper body for next walking period. The immediate compensation scheme corrects the pose of upper body to let the swing of upper body keep stably with the walking trajectory. The experimental results show that the suggested control system can make the biped robot to walk successfully on unknown slopes. For NAO robot, the proposed method

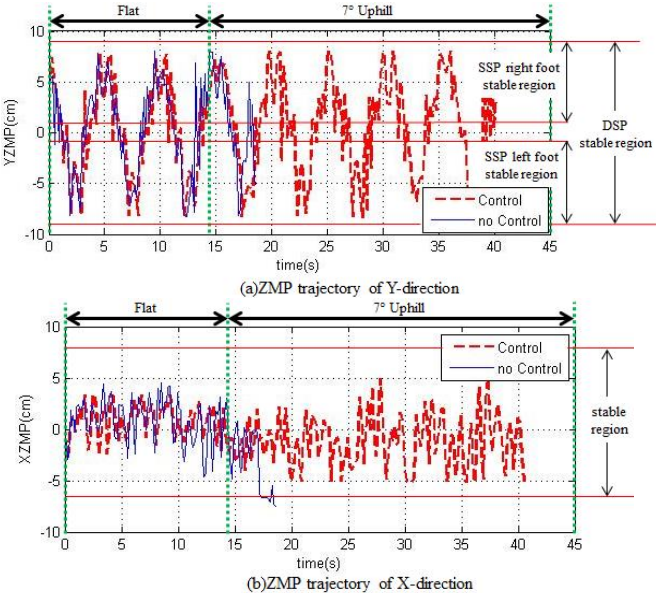


Figure 8. Recorded ZMP trajectory on X-direction and Y-direction.

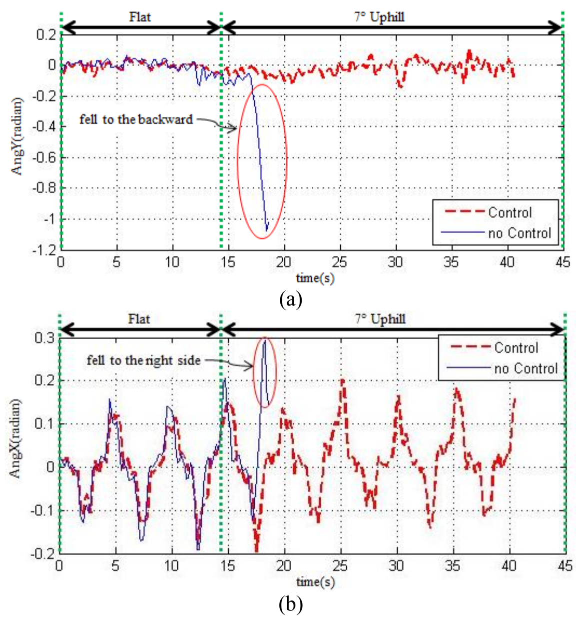


Figure 9. Recorded sensory data during bipedal walking: (a) Y-direction rotation angle (AngY), (b) X-direction rotation angle (AngX).

can allow it to walk on unknown slopes between -7° to 7°. The method can be applied to other biped robot in general without other special sensors.

In the future, we will build an accurate relationship between variation of sensing information and effect of compensation control in order to directly correct walking pattern. We will use the foot force sensors to detect the force of the swing as foot landing, and add the landing controller to reduce the disturbance from impact of swing as foot landing. It is hoped that the time of DSP in real environment can be shortened.

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