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Dynamically Adapt to Uneven Terrain Walking Control for Humanoid Robot

WEI Hui[1, *], SHUAI Mei[2], WANG Zhongyu[1]

1 *School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing 100191, China*
2 *School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China*

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Abstract: Dynamically adapt to uneven ground locomotion is a crucial ability for humanoid robots utilized in human environments. However, because of the effect of current pattern generation method, adapting to unknown rough ground is limited. Moreover, to maintain large support region by four-point contact during the landing phase is usually a key problem. In order to solve these problems, a landing phase control and online pattern generation in three dimensional environments is proposed. On the basis of robot-environment non-planar interactive modes, a method of landing control based on optimal support region is put forward to realize stable four-point contact by flexible foot, and a controller is employed to adapt to the changes of ground without using prior knowledge. Furthermore, an adaptable foothold planning is put forward to the online pattern generation considering walking speed, uneven terrain, and the effect of lateral movement to the locomotion stability. Finally, the effectiveness of landing control and online pattern generation is demonstrated by dynamic simulations and real robot walking experiments on outdoor uneven ground. The results indicate that the robot kept its balance even though the ground is unknown and irregular. The proposed methods lay a foundation for studies of humanoid robots performing tasks in complex environments.

Key words: humanoid robots, landing control, online gait generation, uneven terrain

1 Introduction

Humanoid robots have been developed rapidly. In consideration of humanoid robots are expected to work in environment where humans live and work, they should walk not only on flat ground[1] or stairs[2] but also uncertain uneven ground[3–5]. The problems of controlling a dynamic humanoid robots to walk on rough terrain include many sub-problems, including sensing the state of itself and terrains, landing control and planning gait pattern at touchdown time. For stable humanoid robot locomotion on uneven ground, it is important to obtain the information and use the information intelligently to generate appropriate motions by using adequate control algorithms. When walking on uneven ground, the motion planning and landing foot control cannot be ignored to achieve a stable locomotion. That is why we proposed walking control method for humanoid robots adapted to uneven terrain.

To get better mobility and stability of humanoid robots on rough terrain, the concept of landing control has also been expanded along with applications of diverse control schemes. Human ankle joints and foot ligaments are so flexible that the landing foot can easily adapt themselves to almost all uneven ground and make large contact areas with the ground. FUMIYA, et al[6], investigated a stabilization method for a biped robot without soles, which can remain upright by continuously stepping on the appropriate position. But to make a robot work in human environment, they should walk and stand upright with soles. MORISAWA, et al[7], studied the environment modes between the soles and the environment, e.g., the ground. Based on the information of the sensors, the landing adjustment was decomposed into the following four modes: heaving, rolling; twisting, pitching, as shown in Fig. 1. Most of the past researches on uneven terrain only studied control method of first three contact environment modes for the soles of their robots are rigid and rectangular plane. For example, OHASHI, et al[8], proposed a walking stabilization method based on environment modes on flat foot. PARK, et al[9], proposed a landing control method for biped robots to walk on unpaved dirt roads littered with little rocks in simulation world. The terrain information was represented by a terrain matrix, assuming the contact sensors are installed at the flat sole in his research. WANG, et al[10], proposed a landing control method based on first three contact environment modes. However, it is very hard for those flat soles to realize non-planar four points contact with large support region on the uneven terrain expressed in Fig. 1 (d). Meanwhile the settings of the rough terrains are

* Corresponding author. E-mail: weihuitang@gmail.com
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very limited and there have been few studies to investigate the possibility of dynamics based walking on rough terrain.

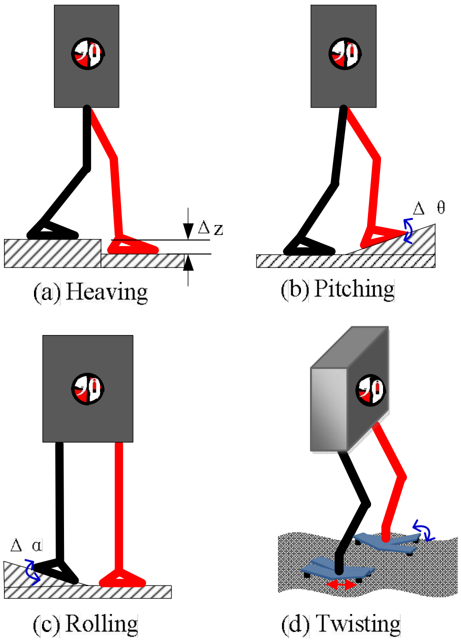


Fig. 1. Environmental mode

Therefore, a landing control based on flexible foot to realize large support region four-point contact was introduced. Humanoid robot BHBIP used in this paper can realize three dimensional close contacts with the uneven ground, because of its flexible foot system. So the landing foot of BHBIP can always find a stable contact mode, adapting to the different uneven terrain, as shown in Fig. 1 (d).

In addition, the real time pattern generation was required during walking on uneven terrain. Although many papers have been published on the walking pattern generation for humanoid robots locomotion on uneven ground, most of them were concerned with offline pattern generation or feedback control. Only a few researchers studied online pattern generation, for example, KAJITA, et al[11–12], realized online gait planning applying three dimensional linear inverted pendulum mode that moves only in sagittal plane. LIM, et al[13], proposed 'quasi real-time' walking pattern generation using FFT based dynamically stable motion construction method online. LORCH, et al[14], also realized online gait planning on biped robot that moves only in sagittal plane using stereo vision sensor. YAGI, et al[15], proposed generating obstacle avoiding footprint generation method in simulation world. NISHIWAKI, et al[16], proposed a real-time walking pattern generation method that made a humanoid robot to follow specified footprint locations online by dynamically stable mixture pre-designed motion trajectories. Therefore a method of three dimensional online pattern generation involving adaptable foothold planning was introduced. The effect of lateral motion to the stability of locomotion is also described and short calculation time made it possible to generate viable gait patterns on the physical prototype.

The organization of this paper is as follows. In section 2, the platform of humanoid robot with flexible foot is presented, and the model of uneven terrain used in this paper is defined in section 3. In section 4, the method of the landing control is outlined. Section 5 describes how to generate the gait pattern online. Experiments were conducted using humanoid robot BHBIP, and the results are provided in section 6, followed by the conclusions in section 7.

2 Overview of the Robot Platform: BHBIP

BHBIP is a humanoid robot which has 31 degrees of freedom (DOFs), 6×2-DOF in leg, 3-DOF in waist, and 8×2-DOF in foot. BHBIP is 800 mm height, and has less mass than 15 kg. Pentium M-1.4GHZ embedded PC104 is equipped on humanoid robot BHBIP as a main controller, and its operating system is Windows XP. There are accelerometers on the soles and IMU (inertial measurement unit) on the torso to obtain the attitude information of robot. DC motor and harmonic drive reduction gear mechanism is attached as an actuator for joint in leg, and cable driven system (DC motor + reduction gear + pulley) for joints in foot. We also developed servo controller for each joint motor position feedback control, as shown in Fig. 2 (c).

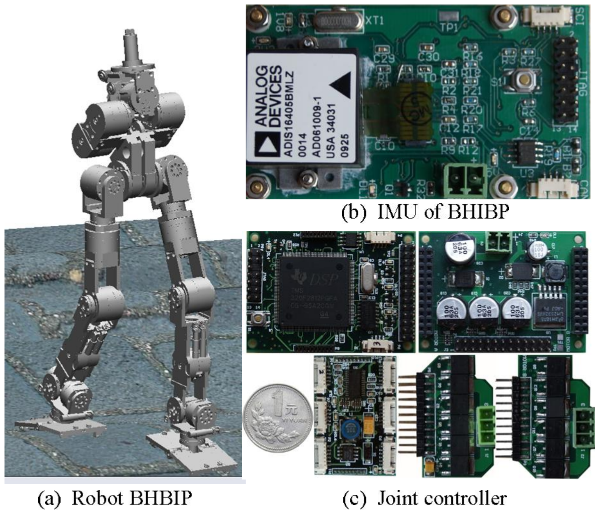


Fig. 2. Overview of the humanoid robot BHBIP

BHBIP can adapt to the uneven terrain automatically using flexible foot system, which occupies 8-DOF (4 DOF for rotation and 4 DOF for translation). Each flexible foot consists of four small planes, which connect to each other by universal coupling joints. Each part of flexible foot has a movable rubber nail below, so the contact motion between the foot and the ground is modeled as four-point contact. The connecting points between the flexible foot and irregularly protruded uneven surface would be controlled actively in landing phase using sensors in the rubber nail to diminish the interference and to increase support region for locomotion stability.

3 Irregularly Uneven Terrain

In the daily life, there are various types of uneven ground on which humanoid robots need to walk, and the walking pattern should be changed depending on the difference of morphology of the ground.

For example, when walking on large rough terrain such as staircase or steep slope, humans should know the state of the terrain in advance by the visual information. Based on environment information, humans find the appropriate landing position trajectory for stable locomotion.

On the contrary, there is another terrain, on which human walk stably without precise sensing of the ground state. The fluctuation of this type uneven terrain is always relatively small compared to the size of the body, such as unpaved dirt roads, mountain areas, generally littered with convex and concave. The inclination angle of this type ground changes randomly, resulting in irregular contact points in height with the feet. Those terrains are the ones we treated in this paper, and the following proposed control approach is based on them.

The uneven terrains addressed in this paper are classified into three groups: 1) unknown and uneven level terrain, 2) unknown and uneven up slope, and 3) unknown and uneven down slope, as shown in Fig. 3.

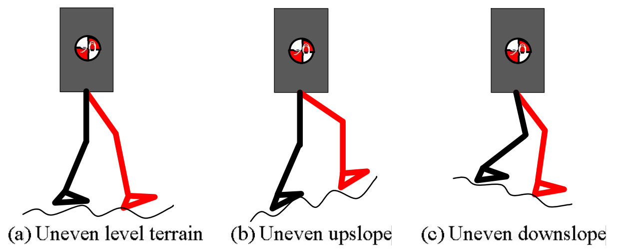


Fig. 3. Three kinds of uneven terrain considered in this paper

In order to adapt to the first class unknown terrain, the landing phase should be controlled to increase locomotion stability by distributing the contact points optimally in a feedback manner.

For the second and third class terrains, adaptation to those unknown inclination was achieved by combining an active balancing controller based on the velocity measurement of center of mass with respect to IMU and the landing phase control.

4 Landing Control

This section explains the description of robot-environment interactive modes, and principle of landing control based on optimal support region. Furthermore, a controller for landing phase is employed to adapt to the changes of ground without using prior knowledge.

4.1 Robot-environment interactive modes

The contact modes between the foot and the ground consist of swing phase, attaching phase, and sliding phase. Swing phase indicates the state of swing foot in single support phase. During attaching phase, the support foot attached the ground with no sliding. Sliding phase is the most important one of contact modes, describing the dynamic process of swing foot swapping to supporting foot. This leads to the following definition.

Definition: Landing control indicates dynamic control from swing phase to attaching phase.

Because of four rubber nails attached underneath the flexible foot system as shown in Fig. 4, a nonlinear compliant contact model is used to model contact phenomenon. Considering that the material used for foot pads has a nonlinear stiffness in the vertical direction, each of the four potential contact points has identical nonlinear spring and damper units.

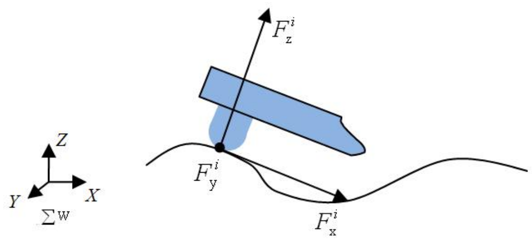


Fig. 4. Contact model between the flexible foot and ground

During the sliding phase, the reaction forces $\boldsymbol{F}^i$ applied on the rubber nails is modeled as

$$\boldsymbol{F}^i = \begin{pmatrix} F_x^i \\ F_y^i \\ F_z^i \end{pmatrix} = \begin{pmatrix} -\mu_n F_z^i \,\mathbf{sgn}(\dot{x}) \\ -\mu_n F_z^i \,\mathbf{sgn}(\dot{y}) \\ K_n\left(z_r\left(x^i, y^i\right) - z^i\right) - B_n \dot{z}^i \end{pmatrix}, \tag{1}$$

where K_n, B_n are the stiffness, damping coefficient, respectively; $z_r\left(x^i, y^i\right)$ is the function of x^i, y^i, $z_r\left(x^i, y^i\right)=0$ when the ground is horizontal; μ_n is the coefficient of dynamic friction.

At the end of landing control, the sliding velocity of the landing foot becomes zero. Then the contact model can be modeled as the spring and damping systems：

$$F_x^i = K_t\left(x_0^i - x^i\right) - B_t \dot{x}^i, \tag{2}$$

$$F_y^i = K_t\left(y_0^i - y^i\right) - B_t \dot{y}^i, \tag{3}$$

where K_t, B_t are associated the stiffness and damping coefficients of the nonlinear spring and damping model respectively

4.2 Principle of landing control based on optimal support region

The humanoid robot moves into the sliding phase when a foot makes an initial contact with the ground. Let $\boldsymbol{p}_{\text{ankle}} = (x_{\text{ankle}}, y_{\text{ankle}}, z_{\text{ankle}})^{\text{T}}$ be the ankle position in the world frame as shown in Fig. 5. The position of rubber nail in flexible foot system can be described as Eq. (4) based on sensor feedback information:

$$\boldsymbol{P}^i = \boldsymbol{R}_{\text{x}}(\theta_i)\boldsymbol{R}_{\text{y}}(\phi_i)\boldsymbol{r}_i + \boldsymbol{P}_{\text{ankle}}, \tag{4}$$

where $\boldsymbol{R}_{\text{x}}(\theta) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$,

$$\boldsymbol{R}_{\text{y}}(\phi) = \begin{pmatrix} \cos\phi & 0 & \sin\phi \\ 0 & 1 & 0 \\ -\sin\phi & 0 & \cos\phi \end{pmatrix},$$

$$\boldsymbol{r}_i = \begin{pmatrix} (-1)^i L_{\text{osh}} \\ (-1)^{2.5-i}(L_{\text{osv}} - d_i) \\ -L_{\text{nail}} \end{pmatrix},$$

$i = 1,2,3,4$ denote four contact points; $\boldsymbol{R}_{\text{x}}(\theta)$, $\boldsymbol{R}_{\text{y}}(\phi)$ are the rotational matrices of pitch and roll motion respectively; $\phi_i = f_1(\beta_i)$, $\theta_i = f_1(\alpha_i)$, $d_i = f_2(\gamma_i)$ indicate the relation among the motor angle measured in position sensors and pitch angle, roll angle, displacement of the rubber nail of flexible foot; α_i, β_i, γ_i are motor angle measured in position sensor of pitch motion, roll motion, and transition motion respectively; $L_{\text{osv}}, L_{\text{osh}}$ describe the displacement among the rubber nail with the center of the flexible foot, while L_{nail} denotes the height of the rubber nail.

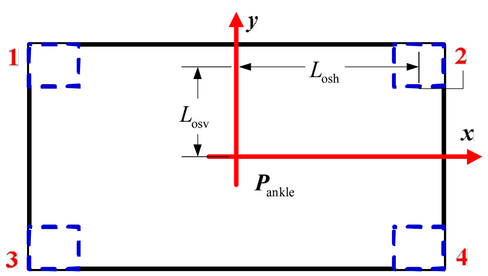


Fig. 5. Sole model and contact points

In section 4.1, we introduced the contact force model, which can be measured based on the acceleration sensors. Let $\boldsymbol{F}^i = (F_{\text{x}}^i, F_{\text{y}}^i, F_{\text{z}}^i)$ be the feedback contact force on rubber nail i. Then the position of center of press (COP) $\boldsymbol{P}_{\text{COP}}$ becomes

$$x_{\text{COP}} = \frac{\sum \hat{F}_z^i \cdot p_x^i}{\sum \hat{F}_z^i}, \tag{5}$$

$$y_{\text{COP}} = \frac{\sum \hat{F}_z^i \cdot p_y^i}{\sum \hat{F}_z^i}, \tag{6}$$

where $\hat{\boldsymbol{F}}^i = \begin{pmatrix} \hat{F}_{\text{x}}^i & \hat{F}_{\text{y}}^i & \hat{F}_{\text{z}}^i \end{pmatrix}^{\text{T}} = \left(\boldsymbol{R}_{\text{x}}(\theta_i)\boldsymbol{R}_{\text{y}}(\phi_i)\right)^{-1}\boldsymbol{F}^i$.

Assumed that the convex hull of the support polygon created by contact points is $\boldsymbol{S}$, and then the principle of landing control translate to support region optimization problem on the condition that COP within the support region. Details are shown as follows:

$$\max \frac{1}{2}\left(p_{\text{x}}^3 - p_{\text{x}}^1\right)\left(p_{\text{x}}^4 + p_{\text{x}}^2 - 2p_{\text{x}}^1\right) + \left(p_{\text{y}}^3 - p_{\text{y}}^1\right)\left(p_{\text{y}}^4 + p_{\text{y}}^2 - 2p_{\text{y}}^1\right), \tag{7}$$

$$\text{s. t.} \begin{cases} x_{\text{COP}} \geqslant \max\left(p_{\text{x}}^1, p_{\text{x}}^3\right), \\ x_{\text{COP}} \leqslant \min\left(p_{\text{x}}^2, p_{\text{x}}^4\right), \\ y_{\text{COP}} \geqslant \max\left(p_{\text{y}}^2, p_{\text{y}}^4\right), \\ y_{\text{COP}} \leqslant \min\left(p_{\text{y}}^1, p_{\text{y}}^3\right). \end{cases}$$

The following principles are suggested to generate motions of landing foot when first point contact is made. Among many possible approaches of rotational and transitional motions of flexible foot, the one that is expected to form the largest support region should be selected. The rotational and transitional motions of flexible foot continue until four contact points attaching to the ground stably. Rotational and transitional motions should be made ensuring that the COP is inside the resulting support region.

The control strategy can be implemented depending on the foot contact mode. Considering the representative cases of ground-foot contact shown in Fig. 6, the following flowchart Fig. 7 will show this process more clearly.

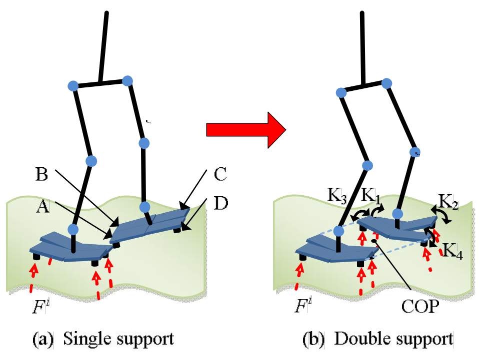


Fig. 6. Contact mode of landing phase

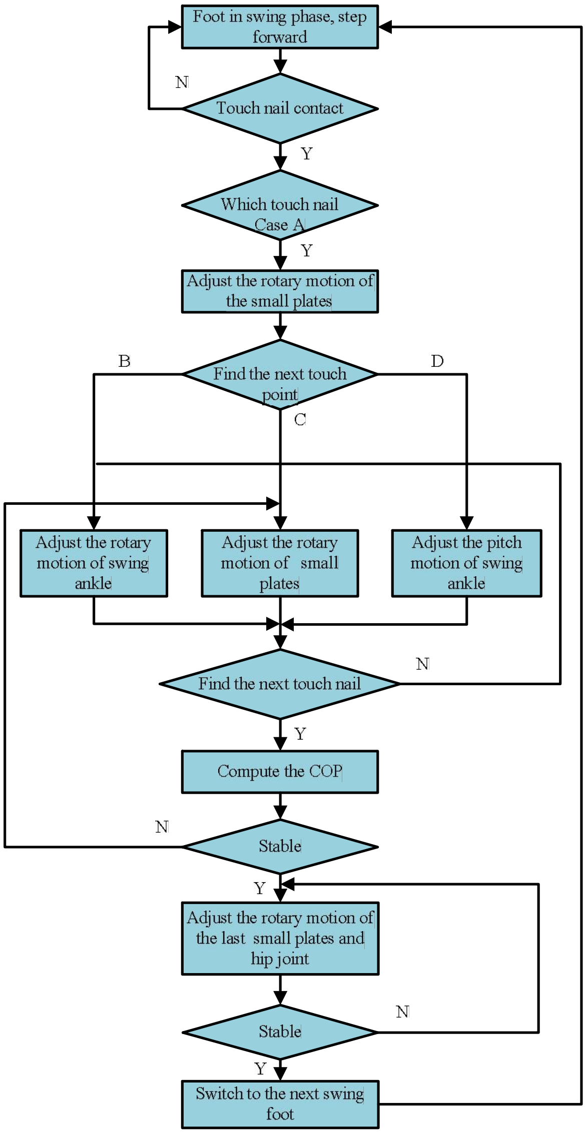


Fig. 7. Flowchart of the landing process for secure footings

When swing foot makes an original contact with the uneven ground at plane A, for example, the rotational motion of flexible foot should move as quickly as possible to find a second contact point and stabilize the robot in the forward direction. The most economical way to find the next support point is making a rotational motion K_1, and then the next contact will occur at plant C. Meanwhile the second contact is generating, the rubber nail moves forward or backward to acquire larger support region. The rotational and transitional motions of flexible foot continue until four contact points attaching with the ground, so the planes rotates around the axes K_2 and K_4. This rotational motion will result in a contact at the location corresponding to plane B or D. Thus, all the four contact points are made, forming a curved surface. Although this is an ideal case, it describes how the contact points forming a larger support region and how a stable footing becoming secured on the ground.

4.3 Controller for landing phase

When a swinging foot contacts the ground too early or late for irregularities of ground, a large impact force or tipping moment, in general, is generated. It is very important to regulate those factors, so a controller for landing phase control is analyzed in this section.

4.3.1 Control for uneven level terrain

The swing foot trajectory is always generated online in the last step, assuming that the ground to be level. However, the real footprint may be higher or lower than the assumed one. In the case swing foot lands on the ground faster than the designed time, it means that actual foothold is higher than the assumed surface. Conversely, the foot lands on the ground slowly when the actual foothold is lower. Accompany with the moment of tipping forward increase, the robot will fall over forward.

If there is no controller to adjust this deviation, the robot may lose its balance. So a landing control is proposed to reduce this influence online. In case when the swing foot lands on the ground earlier, the flexible foot should pitch down so as to lift the robot. The adjustment $\Delta \boldsymbol{q}^i$ of rotational motion of flexible foot system to realize the landing phase is given as follows:

$$\Delta \boldsymbol{q}^i = K_c \boldsymbol{J}^{-1}\left(\boldsymbol{q}^i\right)\Delta \boldsymbol{Z}^i + K_f \boldsymbol{F}^i, \tag{8}$$

where K_c, K_f are coefficients; $\Delta \boldsymbol{Z}$ describes distance between the landing position and rubber nails of robot, which can be estimated based on forward kinematic; $\boldsymbol{J}$ is Jacobin matrix, which describes adjustment of joints; $\boldsymbol{F}^i$ indicates the reaction force applied on rubber nail referred in section 4.1.

4.3.2 Control for slopes

Conceding that a humanoid robot walks in the complex environment, the slope of the terrain will be an important factor of the locomotion stability. Therefore, a controller based on the slope of terrain is proposed to increase the adaptability to uneven ground. The control law can be depicted as follows:

$$\Delta \boldsymbol{q}^{\mathrm{i}} = \boldsymbol{K}_{\mathrm{slope}} \Delta \theta_{\mathrm{slope}}, \tag{9}$$

where $\Delta \boldsymbol{q}^{\mathrm{i}}$ is the joint adjustment of robot; $\boldsymbol{K}_{\mathrm{slope}}$ is coefficients matrix; $\Delta \theta_{\mathrm{slope}}$ describes the ground slope, which can be estimated based on joints position.

5 Online Walking Pattern Generation

Humanoid robot has complicated dynamics model. Because of the high cost of calculating the dynamics, dynamics walking demands high computation resource for real-time implement. In order to apply an online pattern generation method to real robot system, the calculator time for pattern generation should be quick enough, and the trajectory should be simple formed with smooth property.

Inverted pendulum model is widely studied in bipedal locomotion, yet it captures major characteristics of walking. We begin with a simple 3D linear inversed pendulum model of walking, as show in Fig. 8, consisting of alternating single and double-support phases.

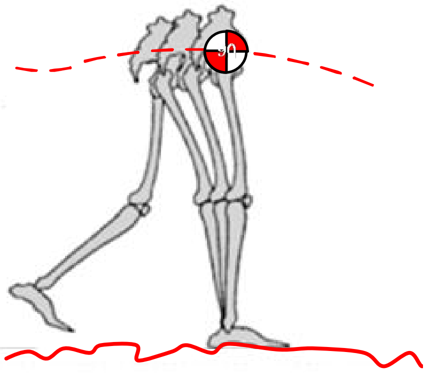


Fig. 8. Inverted pendulum model

Given the dominant mass M is the center of mass (COM) of the body, which was placed at the hip. We initially consider an ideal gait, concentrating on the theoretical consequences of such a gait on the transition between inverted pendulum phases:

$$\ddot{X}_c = \frac{g}{Z_c - z_p}\left(X_c - x_p\right), \tag{10}$$

$$\ddot{Y}_c = \frac{g}{Z_c - z_p}\left(Y_c - y_p\right), \tag{11}$$

where X_c, Y_c, Z_c describe position of COM in world frame respectively, while $\ddot{X}_c, \ddot{Y}_c$ denote the acceleration and x_p, y_p, z_p indicate the position of COP.

Let m be the mass of free foot, then taking the effect of the free leg and the reaction force of flexible foot into consideration. Therefore, the trajectory of COM can be specified by

$$\ddot{X}_c = \frac{g}{Z_c - z_p}\left(X_c - x_p\right) + \mathbf{F}_{\text{free\_}x}\left(t, x_p, z_p\right), \tag{12}$$

$$\ddot{Y}_c = \frac{g}{Z_c - z_p}\left(Y_c - y_p\right) + \mathbf{F}_{\text{free\_}y}\left(t, y_p, z_p\right), \tag{13}$$

where $\mathbf{F}_{\text{free\_}x}\left(t, x_p, z_p\right)$, $\mathbf{F}_{\text{free\_}y}\left(t, y_p, z_p\right)$ describe effect of free foot to COM respectively, which was determined by the trajectory of foot in swing phase.

In the following, a novel method for the foothold planning is introduced. And then a way to generate the trajectory of free foot in Cartesian coordinate based on the adaptable foothold is proposed.

5.1 Adaptable foothold planning

Humans always adjust their steps to increase the stability of locomotion, especially on uneven ground. However, the step length was always fixed in the past research and 'Direct placement' was widely used. Although direct placement generally provided high accuracy during a single step, it could not control several steps in succession especially in the case of large discrepancy. The robot may tip over entirely, because of unsuitable foothold. Therefore, a method for controlling the step length based on the walking speed is introduced in this section.

First, the definition of step length is given as follows.

Definition: Step length refers to the distance traveled by the body while the foot is on the ground as shown in Fig. 9, specified as

$$L_{\text{step}} = L_{\text{sp}} + L_{\text{sw}} = v_{\text{sp}} T_{\text{sp}} + v_{\text{sw}} T_{\text{sw}}, \tag{14}$$

where $v_{\text{sp}}, v_{\text{sw}}$ are the average velocities of the COM in swing phase and stance phase respectively; $T_{\text{sp}}, T_{\text{sw}}$ are the duration of the swing and stance phase respectively.

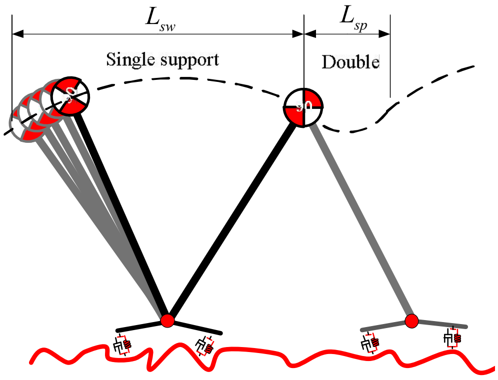


Fig. 9. Definition of step length during a gait cycle

Then, take eyes to the method to plan the adaptable foothold according to COM velocity and uneven terrain. The robot will decelerate when positioning the foot farther; furthermore the robot will accelerate at the case of positioning the foot closer. The easiest method to plan footprint is to make the foot movement twice as the desired torso motion in one step. However, this method turned out to generate unnatural and inefficient footprint in many cases.

In order to generate efficient foothold and make sure that the state of COM is close to the designed one, we used the following control method to design forward and lateral position of the foot at touchdown as shown in Fig. 10, which is specified by

$$x_{\text{nex\_p}} = x_p + T_{\text{sw}}\dot{x}_{\text{sw}} + K_x\left(\dot{x}_{\text{sw0}} - \dot{x}_d\right), \tag{15}$$

$$y_{\text{next\_p}} = y_p + T_{\text{sw}}\dot{y}_{\text{sw}} + K_y\left(\dot{y}_{\text{sw0}} - \dot{y}_d\right), \tag{16}$$

where $\dot{x}_{\text{sw}}, \dot{y}_{\text{sw}}$ are expected speeds in swing and stance phase respectively; $\dot{x}_{\text{sw0}}$, $\dot{y}_{\text{sw0}}$ denote the present velocity of COM at touchdown time; While, $\dot{x}_{\text{d}}$, $\dot{y}_{\text{d}}$ are designed ones; $K_{\text{x}}, K_{\text{y}}$ are empirically determined gains, which can be optimized by learning algorithm.

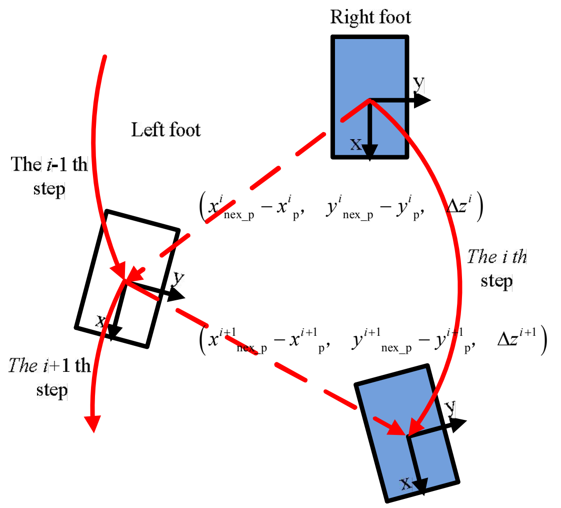


Fig. 10. Foothold planning in forward and lateral plane

5.2 Trajectory plan of free foot in Cartesian coordinate

Locomotion is no longer limited in horizontal plane in this paper, and the method of generating foot trajectory that realizes three-dimension movement is discussed. Swing foot moves from the present foothold to next designed one, as shown in Fig. 10.

In order to generate a smooth trajectory and reduce the collision between the ground and the foot at touchdown time, swing foot trajectory should satisfy the following boundary constraint:

$$\begin{cases} x_{\text{a}}(0) = x_{\text{next\_p}}, x_{\text{a}}(T_{\text{sw}}) = x_{\text{p}}, \\ \dot{x}_{\text{a}}(0) = 0, \dot{x}_{\text{a}}(T_{\text{sw}}) = 0, \\ y_{\text{a}}(0) = y_{\text{next\_p}}, y_{\text{a}}(T_{\text{sw}}) = y_{\text{p}}, \\ \dot{y}_{\text{a}}(0) = 0, \dot{y}_{\text{a}}(T_{\text{sw}}) = 0, \\ z_{\text{a}}(0) = 0, z_{\text{a}}(T_{\text{sw}}) = 0, \\ \dot{z}_{\text{a}}(0) = 0, \dot{z}_{\text{a}}(T_{\text{sw}}) = 0. \end{cases} \tag{17}$$

To simplify the analysis, we supposed the foot trajectory in Cartesian coordinate as follows:

$$x_{\text{a}}(t) = \left(x_{\text{next\_p}} - x_{\text{p}}\right)\left[\frac{t}{T_{\text{sw}}} - \frac{1}{2\pi}\sin\left(2\pi\frac{t}{T_{\text{sw}}}\right)\right] + x_{\text{p}}, \tag{18}$$

$$y_{\text{a}}(t) = \left(y_{\text{next\_p}} - y_{\text{p}}\right)\left[\frac{t}{T_{\text{sw}}} - \frac{1}{2\pi}\sin\left(2\pi\frac{t}{T_{\text{sw}}}\right)\right] + y_{\text{p}}, \tag{19}$$

$$z_{\text{a}}(t) = \frac{h_{\text{hall}}}{2}\left[1 + \sin\left(\frac{2\pi}{T_{\text{sw}}}\left(t - \frac{T_{\text{sw}}}{4}\right)\right)\right]. \tag{20}$$

Now, the effects of the free foot to COM based on above definition can be specified as follows:

$$F_{\text{free\_x}}\left(t, x_{\text{p}}, z_{\text{p}}\right) = \frac{1}{T_c^2}\left[L_1 x_{\text{p}} + L_2(x) z_{\text{p}} + f(t, x)\right], \tag{21}$$

$$F_{\text{free\_y}}\left(t, y_{\text{p}}, z_{\text{p}}\right) = \frac{1}{T_{\text{c}}^2}\left[L_1 y_{\text{p}} + L_2(y) z_{\text{p}} + f(t, y)\right], \tag{22}$$

where $T_{\text{c}} = \sqrt{\dfrac{Z_{\text{c}} - z_{\text{p}}}{g}}$,

$$L_1 = \frac{m T_{\text{sw}}^{\ 2}}{4\pi M}\cos\frac{2\pi t}{T_{\text{sw}}} - \frac{m}{M + m},$$

$$L_2(y) = \frac{m h_{\text{hall}} T_{\text{sw}}^{\ 2}\left(y_{\text{next\_p}} - y_{\text{p}}\right)}{16\pi^3 M g}\sin\frac{2\pi t}{T_{\text{sw}}},$$

$$f(t, y) = \frac{mt}{M T_{\text{sw}}} + \frac{m T_{\text{sw}}^{\ 2}\left(y_{\text{next\_p}} - y_{\text{p}}\right)}{8\pi^3 M g} \times \left(\frac{h_{\text{hall}}}{2} - 1\right)$$

$$\cos\frac{2\pi t}{T_{\text{sw}}} \cdot \sin\frac{2\pi t}{T_{\text{sw}}}.$$

5.3 COM trajectory planning

Solve the differential Eqs. (23) and (24), the COM trajectory can be explained as

$$X_{\text{c}}(t) = X_{\text{c}}(0)\cosh\left(\frac{t}{T_{\text{c}}}\right) + T_{\text{c}}\dot{X}_{\text{c}}(0)\sinh\left(\frac{t}{T_{\text{c}}}\right) + C_{\text{x}}\left(t, x_{\text{p}}\right), \tag{23}$$

$$Y_{\text{c}}(t) = Y_{\text{c}}(0)\cosh\left(\frac{t}{T_{\text{c}}}\right) + T_{\text{c}}\dot{Y}_{\text{c}}(0)\sinh\left(\frac{t}{T_{\text{c}}}\right) + C_{\text{y}}\left(t, y_{\text{p}}\right), \tag{24}$$

where $X_{\text{c}}(0), \dot{X}_{\text{c}}(0)$ are the initial states of X_c; $C_{\text{x}}\left(t, x_{\text{p}}\right)$ is the integral term that describes the influence factor of $F_{\text{free\_x}}\left(t, x_{\text{p}}, z_{\text{p}}\right)$, and so does Y_{c}.

6 Experimental Result

6.1 Simulations

A biped robot model with 31-DOF is established to evaluate the landing control and gait generation method on rough terrain. The rough terrains model considered in this section, whose differences of morphology are small relative to the body. We classified this kind of uneven terrains into the following three groups and evaluated the effectiveness of proposed method in connection of certain terrain.

6.1.1 Walking on uneven level terrains

The rough terrains used in the simulation are constructed by the 3rd order polygonal interpolation curve. The interpolation points $(X(i), Z(i))$ of the ground position are defined by the following equations:

$$\begin{pmatrix} X^{(i)} \\ Z^{(i)} \end{pmatrix} = \begin{pmatrix} X^{(i-1)} + S_x R \\ Z^{(i-1)} + S_z (R - 0.5) \end{pmatrix}, \tag{25}$$

where $X^{(0)} = 0, Z^{(0)} = 0$; R is the random number from 0 to 1; S_x and S_z are the constant values that determine the degree of uneven of the ground.

Fig. 11 shows the transition of walking on uneven terrain in relation to the unevenness degree S_x =0.01 m, S_z =0.04 m. The robot successfully walked while changing the contact mode between the grounds. Fig. 11 also indicates that the landing flexible foot pitched and the rubber nails moved forward and backward to adapt to convex and concave terrains.

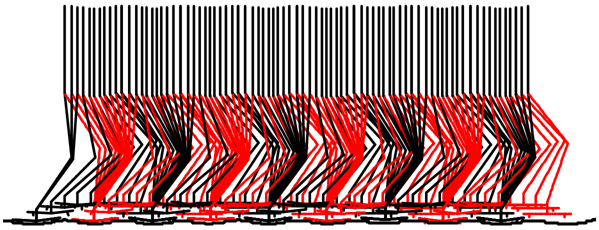


Fig. 11. Transition of walking on uneven terrain

6.1.2 Walking on uneven slope

The uneven slopes are also constructed by the 3rd order polygonal interpolation curve, and the angle of inclination of the ground changes randomly. The interpolation points $(X(i), Z(i))$ of the ground position are defined by the following equations:

$$\begin{pmatrix} X^{(i)} \\ Z^{(i)} \end{pmatrix} = \begin{pmatrix} X^{(i-1)} + S_x R \\ K \cdot X^{(i)} + S_z (R - 0.5) \end{pmatrix}, \tag{26}$$

where K is the slope of the ground curve; K is always negative for down slope, and $K > 0$ for upslope; R is the random number from 0 to 1; $X^{(0)} = 0$, $Z^{(0)} = 0$; S_x, S_z are the constant values that determine the degree of unevenness.

In relation to the unevenness degree S_x =0.01 m, S_z =0.03 m and $K = 0.7$ of uneven upslope, Fig. 12 shows how the robot landing control works during walking on uneven upslope. The robot successfully walked over the uneven terrains, and maintained larger support region four point contacts. While S_x =0.01 m, S_z =0.03 m and $K = -0.7$ for down slope in Fig. 13, the robot walked over while changing the contact mode and footholds.

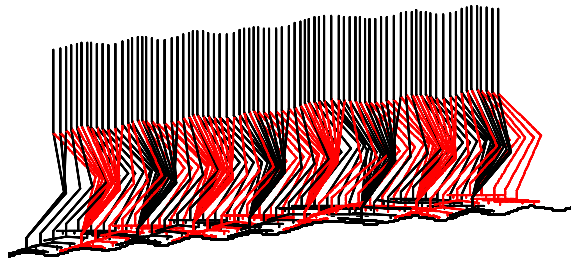


Fig. 12. Transition of walking on uneven upslope

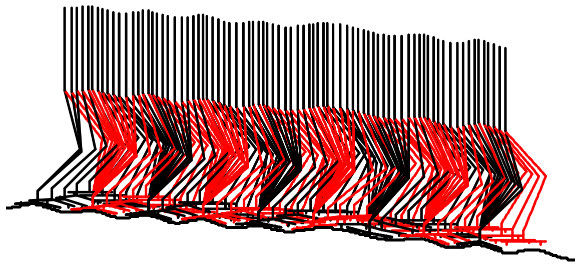
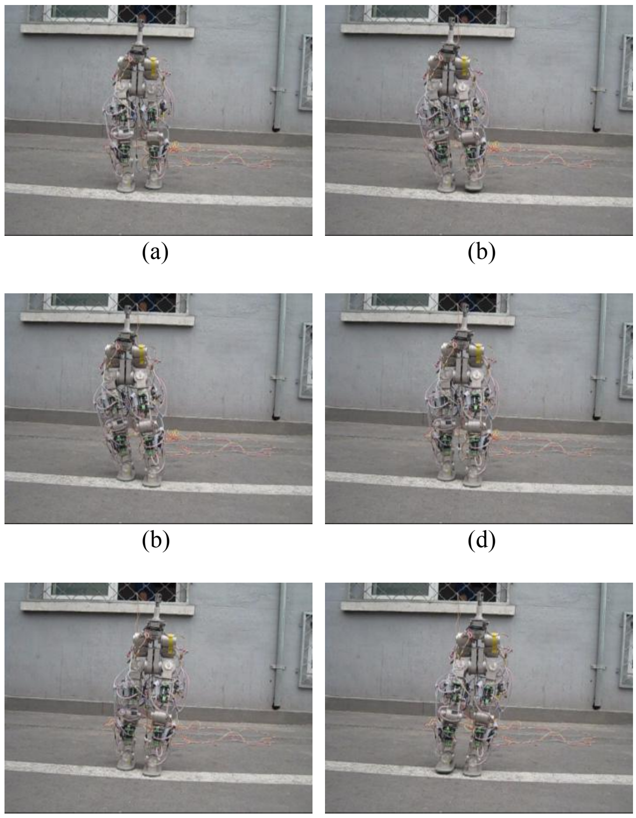


Fig. 13. Transition of walking on uneven down slope

6.2 Experiments on real robot

To evaluate the online gait generation method, we conducted outdoor terrain adaption experiments using our humanoid robot BHBIP introduced in section 2.

The result is shown in Fig. 14. Even though the ground in outdoor environment is unknown and irregular, the robot kept its balance during walking.



(a) (b)

(b) (d)

(e) (f)

(g) (h)

Fig. 14. BHBIP walked in outdoor environment

7 Conclusions

(1) On basis of flexible foot, a novel method of landing control based on optimal support region is employed to realize non-planar four-point contact between the flexible foot and ground. And a controller for landing phase is presented. As a result, the robot can adapt to the changes of ground without prior knowledge.

(2) To increase the stability of locomotion, especially on uneven ground, adaptable foothold planning is employed to the online pattern generation considering walking speed and uneven terrain. And the effect of lateral movement to the stability of locomotion is utilized to gait generation.

(3) With sets of simulations, the effectiveness of landing control is evaluated by 31-DOF biped robot model. The results indicate that the stability of locomotion is improved when the robot walking on specific terrain referred in this paper.

(4) The experiments of real robot BHBIP locomotion on outdoor terrain were implemented. The robot kept its balance even though the ground is unknown and irregular. The results verify the feasibility of online gait generation.

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Biographical notes

WEI Hui, born in 1986, is currently a PhD candidate at *School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing, China*. Her research interests include humanoid robot dynamic walking and control strategy.
Tel: +86-10-82339303; E-mail: weihuitang@gmail.com

SHUAI Mei, born in 1967, is currently an associate professor at *School of Automation Science and Electrical Engineering, Beihang University, Beijing, China*. Her research interests include humanoid robot dynamic walking and control strategy.
Tel: +86-10-82317303; E-mail: shuaimei@gmail.com

WANG Zhongyu, born in 1963, is currently a professor and a doctoral supervisor at *School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing, China*. His research interests include precision measurement technique.
Tel: +86-10- 82338881; E-mail: mewan@buaa.edu.com