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Humanoids Walk with Feedforward Dynamic Pattern and Feedback Sensory Reflection

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Abstract

Since a biped humanoid inherently suffers from instability and always risks itself to tipping over, ensuring high stability and reliability of walk is one of the most important goals. This paper proposes a walk control consisting of a feedforward dynamic pattern and a feedback sensory reflex. The dynamic pattern is a rhythmic and periodic motion, which satisfies the constraints of dynamic stability and ground conditions, and is generated assuming that the models of the humanoid and the environment are known. The sensory reflex is a simple, but rapid motion programmed in respect to sensory information. The sensory reflex, we propose in this paper, consists of the body posture control, the actual ZMP (Zero Moment Point) control, and the landing time control. With the dynamic pattern and the sensory reflex, it is possible for the humanoid to walk rhythmically and to adapt itself to environmental uncertainties. The effectiveness of our proposed method was confirmed by walk experiments of an actual 26 DOF humanoid on an unknown rough terrain and in the presence of disturbances.

1 Introduction

Aging societies in the near future will face a growing need for daily assistance of human activities in the common environments, such as offices, homes and hospitals. In addition to various mechanical and automated equipments for the general assistance, humanoid robots will find their indispensable demands in the close assistance of the humans, since the anthropoid shape allows it to be and move in the environments designed for humans.

Humanoid robots involve many technical issues to be solved, among which stable and reliable biped walk is the most fundamental and yet unsolved with a high degree of reliability. This subject has been studied mainly from the following two technical points of view.

The first approach is to generate a dynamically consistent walking pattern off-line. It is done assuming that the models of robot and environments are available. Takanishi et al. [2], Shin et al. [3], and Hirai et al. [4] have proposed methods of pattern synthesis based on the ZMP (Zero Momnet Point) [1]. The ZMP was originally defined for ground contacts of legs by Vukobratovic [1] as the point in the ground plane about which the total moments due to ground contacts becomes zero in the plane.

It is important to recognize that the ZMP must always reside in the convex hull of the all contact points on the ground plane (In the following, the convex hull is called the stable region), since the moments in the ground plane is caused only by normal forces at the contact points which are always be positive in the upper vertical direction. Therefore, only if the ZMP stays in the stable region, the planned walk motion is dynamically possible for the humanoid. The above previous works first design a desired ZMP trajectory, then derive a hip or body motion that comprises with the ZMP trajectory. Since the body motion is limited, not every desired ZMP trajectory [5] can be achieved. Huang et al. [6] proposed a method to generate smooth body-motion and walk pattern simultaneously considering the ZMP constraints and the limitation of the body-motion.

The second approach is from the controller-design point of view. Furusho et al. [7], Fujimoto et al. [8] have discussed control methods based on the dynamical equations of motion. These methods demand high computation resources for real-time implementation. To ease real-time implementation, some methods were proposed, based on simplified models such as a pendulum model and a static model [4, 9, 10, 11, 12]. Yamaguchi et al. [13] developed a foot mechanism with a shock-absorbing material to adapt to uneven ground surfaces, Kun et al. [14], Hu et al. [15] discussed adaptive control of biped robots using neural networks.

Biological investigations suggest that human's rhythmic walking is the consequence of combined inherent patterns and reflexive actions [16, 17]. The inherent dynamic pattern is rhythmic and periodic. It is considered as an optimal feedforward motion pattern acquired through development in the typical walk environments without disturbances. The reflexive action is a rapid response due to the feedback control using sensory information. This reflexive action determines stability against unexpected events such as external disturbances or ground irregularity.

Although many works have been published on the reflexive control in robotics, most of them concerned on mobile robots and manipulators [18, 19, 20]. Some researchers have introduced the reflexive control to legged robots focusing on the contact and slipping [21, 22, 23]. A biped humanoid requires not only to rhythmic walk in a known environment but also to adapt itself to real-world uncertainties. It is, therefore, essential to design a human-like walk control taking account of the specific dual structure of feedforward and feedback controls.

In this paper, we propose a walk control design of a feedforward dynamic pattern and a feedback sensory reflex for biped humanoids considering their specific structures. The organization of this paper is as follows: In Section 2, we provide the general scheme of control with feedforward dynamic patterns and feedback sensory reflexes. In Section 3, we describe a method to plan an inherent dynamic pattern. In Section 4, we design a sensory reflex consisting of a body-posture control, an actual ZMP control and a landing time control based on sensory information. Experiments were conducted using a 26 DOF humanoid and their results are provided in Section 5, followed by the conclusions in Section 6.

2 Scheme of Walking Control

The humanoid consists of a body, legs, and arms (Fig. 1). Each leg consists of a thigh, shank and foot and has 6 DOF (degrees of freedom): 3 DOF in the hip joint, 1 in the knee joint, and 2 in the ankle joint. Each arm consists of an upper arm, forearm, and hand, and has 7 DOF: 3 DOF in the shoulder joint, 1 in the elbow joint, and 3 in the wrist joint.

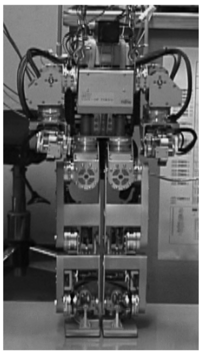


Figure 1: A biped humanoid with 26 DOF's

One acquires his inherent walking patterns through the development and refinement by repeated learning and practice. Without such process, a humanoid has to make the best use of the knowledge of dynamics to generate a rhythmic, dynamic walk-pattern. It is not straightforward to compute the dynamic walk-pattern on-line due to the nonholonomy of the contact constraints. The motion of ZMP in the foot surface can find its equivalence in that of the contact point in rolling fingertip contacts, which is known nonholonomic. The motion of ZMP is governed by the dynamics of the whole body and, therefore, of further complexity. Therefore, the dynamic walk-pattern generation requires an optimization process and stays off-line with common computing resource.

Since the planned dynamic pattern is merely a solution of motion trajectory for the assumed conditions, the issues of stability, robustness, adaptability and so on must be separately considered for the uncertain real environments and the other conditions.

On the other hand, a human can suddenly bend his arm if his hand touched an unexpected hot spot. Such a reflexive action is a rapid response without requiring the exact models of dynamics, and is suitable to deal with environmental uncertainties. So, we propose a sensory reflex to improve the stability for the humanoid in the real environments. The sensory reflex is a local feedback response to environmental uncertainties, and the dynamic pattern is an optimal feedforward motion in the typical walk environments without disturbances. It is therefore undesirable to change the planned dynamic pattern with the exception of environmental uncertainties. In order for a biped humanoid to walk rhythmically and adapt to environmental uncertainties, we proposed a dual structure consisting a feedforward dynamic pattern and a feedback sensory reflex (Fig. 2)

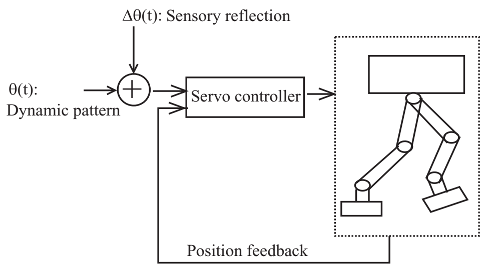


Figure 2: Dual structure of walking control

As shown in Fig.2, $\theta(t)$ is the value of the dynamic pattern, which is a rhythmic trajectory and will not change during walking. $\Delta\theta(t)$ is the value of the sensory reflex, which is a rapid response to humanoid's sensor information. For example, if the actual environmental conditions are the same as the assumed conditions when generating the dynamic pattern, $\Delta\theta(t)$ is zero, and the humanoid walks as the inherent dynamic pattern; if there are unexpected factors such as unexpected collision during walking, $\Delta\theta(t)$ is not zero, then the humanoid walk as a modified pattern; after the collision, $\Delta\theta(t)$ becomes zero gradually, the robot will return its inherent dynamic pattern again. In the following sections, we discuss the methods of the dynamic walking pattern generation and the sensory reflex control.

3 Dynamic Walking Pattern

To ensure the reliability of walk for a biped humanoid, the inherent walking pattern must satisfy the constraints of dynamic stability. In addition, to be able to walk on various grounds such as level ground, rough terrain and obstacle-filled environments, the ground constraints must be satisfied. We have already proposed a method for planning such walking patterns [6], and briefly outline here.

To simplify the analysis, only sagittal plane walking will be discussed in the following. For a sagittal plane, let vector $\mathbf{X}_F = [x_f(t), z_f(t), \theta_f(t)]^T$ denote each foot trajectory; let vector $\mathbf{X}_B = [x_b(t), z_b(t), \theta_b(t)]$ denote the hip trajectory (Fig. 3). Supposing that the period necessary for one walking step is T_c, the kth walking step begins with the heel of the right foot leaving the ground at $t = kT_c$, and ends with the heel of the right foot touching the ground at $t = (k+1)T_c$. The characteristic constraints of the right foot slope are given by the following equations:

$$\theta_f(t) = \begin{cases} q_{gs}(k) & t = kT_c \\ q_b & t = kT_c + T_d \\ q_f & t = (k+1)T_c \\ q_{ge}(k) & t = (k+1)T_c + T_d \end{cases} \quad (1)$$

where q_b and q_f be the designated slope angles of the right foot as it leaves and lands on the ground (Fig. 3), T_d denotes the interval of the double-support phase, and $q_{gs}(k)$ and $q_{ge}(k)$ are the angles of the ground surface under the support foot.

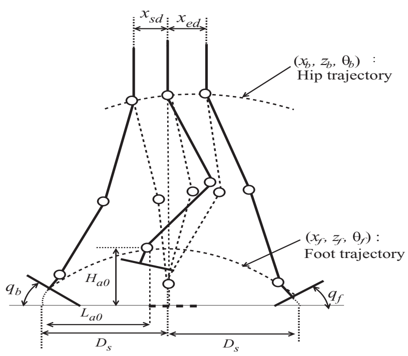


Figure 3: Walking parameters

To generate a smooth trajectory, it is necessary that the second derivatives (accelerations) $\ddot{\theta}_f(t)$ be continuous at all t, including all breakpoints $t = kT_c$, $kT_c + T_d$, $(k+1)T_c$, $(k+1)T_c + T_d$. To solve for the foot trajectory that satisfies constraint (1) and the constraints of second derivative continuity, 3rd order spline interpolation was used [24]. Similarly, $x_f(t)$ and $z_f(t)$ can be obtained. By setting the values of q_b, q_f, $q_{gs}(k)$, $q_{ge}(k)$, and other parameters such as clearance and stride length, different foot trajectories can be produced.

From the viewpoint of stability, it is desirable that the body posture $\theta_b(t)$ is constant when the robot has no waist joint; in particular, $\theta_b(t) = 0.5\pi$ [rad] on level ground. Body motion along the z-axis has little effect on the position of the ZMP. We can specify $z_b(t)$ to be constant, or to vary within a small range. To get high stability and smooth body motion along the x-axis, the following steps were considered:

(1) Generate a series of smooth $x_b(t)$.

(2) Determine the final $x_b(t)$ with a large stability margin

$x_b(t)$ during a one-step cycle can be described by the double-support phase and the single-support phase functions. Letting x_{sd} and x_{ed} denote distances along the x-axis from the hip to the ankle of the support foot at the beginning and the end of the single-support phase, respectively (Fig. 3), the following equation can be obtained:

$$x_b(t) = \begin{cases} kD_s + x_{ed} & t = kT_c \\ (k+1)D_s - x_{sd} & t = kT_c + T_d \\ (k+1)D_s + x_e d & t = (k+1)T_c \end{cases} \quad (2)$$

By using 3rd order spline interpolation, trajectory of $x_b(t)$ that satisfies the constraint (2) and the constraint of second derivative continuity can be obtained. Hence, series of smooth $x_b(t)$ are obtained by setting different values of x_{sd} and x_{ed} within fixed ranges, in particular $0.0 < x_{sd} < 0.5D_s$, $0.0 < x_{ed} < 0.5D_s$. Then, the smooth trajectory $x_b(t)$ with the largest stability margin can be found by exhaustive search calculation.

4 Sensory Reflex

Some previous investigations have studied the control based on sensor feedback, most of them depends on a simplified or a complete robot's model [4, 7, 8, 9, 10, 11, 12]. The sensory reflex proposed in this paper is a rapid response with no explicit modeling. Although the dynamic walking pattern presented in Section 3 satisfies the dynamic stability constraint, the biped robot may tip over when walking on unexpected rough terrain or if pushed by an external force. It is therefore to modify the original dynamic pattern when the humanoid becomes unstable, and return to the original inherent pattern gradually when the humanoid is stable by the sensory reflex.

When the humanoid becomes unstable, the body slants. If the body posture is not recovered in time, the tipping moment becomes large and the slanting increases. During tipping, in general, the ZMP is on the boundary of the stable region. To recovery the stability, the ZMP should be moved into the stable region. In addition, since the ground irregularity is unknown in advance, it is difficult for the foot to land the ground at appropriate time. If the foot lands the ground too fast, a large tipping moment occurs, and the robot will tip backwards immediately. Such events occur in an extremely limited time, and should be dealt with rapidly. Therefore, we proposed a sensory reflex consisting of a body posture control, an actual ZMP control and a landing time control.

4.1 Body Posture Control

The actual body posture is measured by inclination sensors such as accelerometer and angular rate sensors. Since the hip joints are near the body, the most effective way to keep the desired body posture is to control the hip joints (Fig. 4). On the other hand, the hip joint of the swing foot does not affect the body posture. To maintain walking as the inherent pattern, the hip joint of the swing foot should return to its inherent pattern. The hip joint $\Delta\theta_h(t)$ of the body posture control is given as follows:

$$\Delta\theta_h(t) = \begin{cases} \Delta\theta_{actb}(t) & F_z > 0 \\ 0 & F_z = 0 \end{cases} \tag{3}$$

where $\Delta\theta_{actb}(t)$ is the deflection between the actual and the desired body postures. F_z is the foot contact force, which is measured by a foot force sensor. If $F_z > 0$, the foot is the support foot; if $F_z = 0$, the foot is the swing foot.

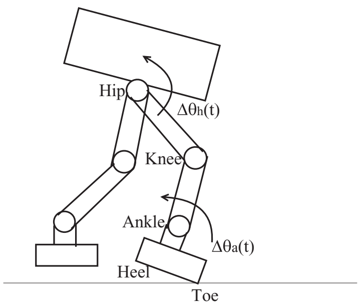


Figure 4: Body posture control and actual ZMP control

4.2 Actual ZMP Control

The actual ZMP is measured by a foot force sensor. For a sagittal plane, generally only the toe or the heel is in contact with the ground during tipping. Viewed from the concept of the ZMP, in those cases, the actual ZMP is on the toe or on the heel, that is, the actual ZMP is on the boundary of the stable region. To avoid having only one edge of the foot contacting the ground, there should be some distance between the actual ZMP and the boundary of the stable region. In the following, this distance during actual walking is called the actual stability margin.

If the actual ZMP is always controlled in the center of the stable region, the actual stability margin is the largest. But in that case, the robot cannot move at high speed. In addition, if the actual stability margin is designated to be larger than the stability margin of the inherent pattern, the inherent walking pattern must always be modified in any cases. A suitable actual stability margin can be the same as the stability margins of the inherent walking pattern, or can be computed according to environmental disturbances [5]. Thereafter, the region with the stability margin is called the valid stable region (Fig. 5).

One effective way to keep the actual ZMP within the valid stable region is to control the ankle joints of the support feet. The ankle joint $\Delta\theta_h(t)$ of the actual ZMP control is calculated using the following equation.

$$\Delta\theta_a(t) = \begin{cases} K_a * d_{zmp}(t) & F_z > 0 \\ 0 & F_z = 0 \end{cases} \tag{4}$$

where $d_{zmp}(t)$ is the distance between the actual ZMP and the boundary of the valid stable region (Fig. 5) and K_a is a coefficient.

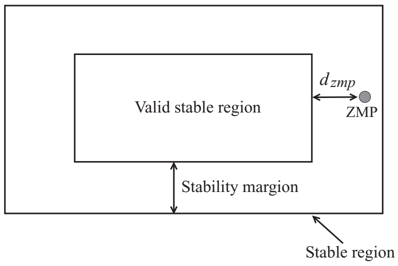


Figure 5: Valid stable region

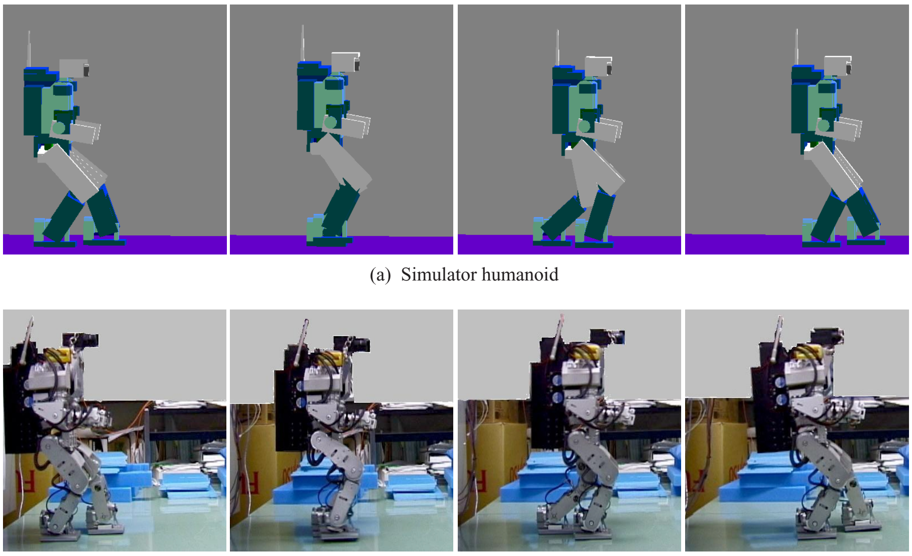
4.3 Landing Time Control

To walk continuously, the transition of the swing foot to the support foot must occur at an appropriate time. If the foot lands the ground too fast, the moment of tipping backward occurs, and the robot will tip backwards. Conversely, if the foot lands on the ground too late, the moment of tipping forwards increases, and the robot will tip forward. To land on the ground on time, the change $\Delta Z_a(t)$ of the foot position along vertical direction is given as follows:

$$\Delta Z_a(t) = \begin{cases} K_f * F_z & t \le T_{land},\ F_z \ge 0,\ F_a < Mr \\ -h & t > T_{land},\ F_a = 0 \\ 0 & t > T_{land},\ F_a >= Mr \end{cases} \tag{5}$$

where K_f is the coefficient, and h is a constant variable, T_{land} is the landing time specified by the inherent pattern. M_r is the weight of the humanoid.

According to equation (5), if the foot lands on the ground too fast, the robot lifts its foot in proportion to the foot contact force; if the foot lands on the ground too late, the robot lowers its foot; if the support foot becomes the single-support foot, e.g. the foot supports the whole humanoid, the foot position returns to its value of the inherent pattern. The on-line change of foot position is achieved by controlling the hip and knee joints according to the kinematics.



(a) Simulator humanoid

(b) Actual humanoid

Figure 7: Walking on a known level ground

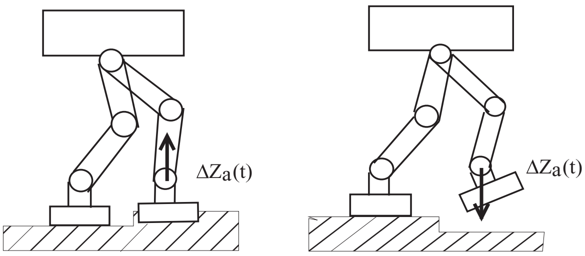


Figure 6: Landing time control by foot position

5 Experimental Examples

The humanoid may tip over during walking, so actual humanoid experiments carrying developing control algorithms are dangerous and costly. It is effective and desirable to verify various control algorithms using a software simulator before using an actual humanoid, especially for some dangerous experiments. Therefore, we have developed a dynamic simulator [25] based on DADS (Dynamic Analysis and Design Systems) and an actual humanoid to test our proposed method.

To evaluate the equivalence of our constructed simulator and the actual humanoid, we did some walking experiments by using the simulator and the actual humanoid robot. Parameters of the simulator are set as the same as the actual humanoid. The humanoid robot has 26 degrees of freedom with a 0.5 [m] height and a 7.5 [kg] weight. Fig. 7 shows the walks on a known level ground with the step length 1.2 [m/step] and step period 1.8 [s/step]. It is known that the biped walking of the actual humanoid was similar to the biped walking of the simulator.

Fig. 8 shows the walks in environments in the presence of a disturbance. The disturbance is assumed to be the unexpected collision force between a pendulum and the humanoid. Different collision forces add on the humanoid with different mass of the pendulum. Using the developed simulator, we can observe that the humanoid can continue walking when hit by a 3.5 [kg] pendulum.

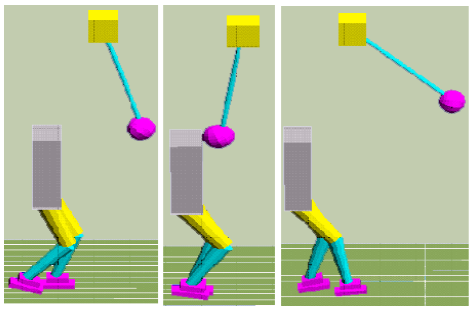
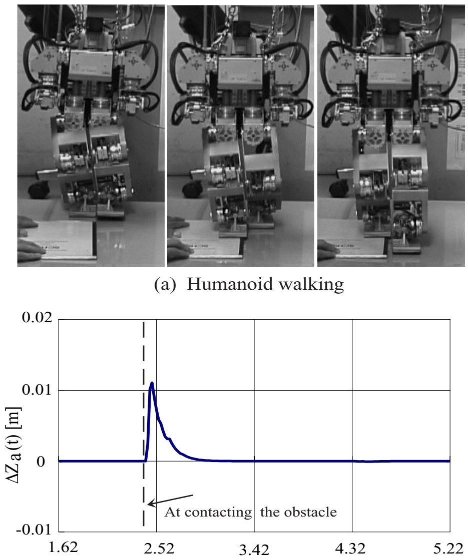


Figure 8: Walking in the presence of disturbance

Fig. 9 shows the experimental results on unknown rigid rough ground with a $\pm$ 0.01 [m] height obstacle. It is known that the humanoid can walk stably by using our proposed walking control. The change of the sensory reflex $\Delta Z_a(t)$ (Fig. 9 (b)) can be explained as follows. If the humanoid walks as the same as the inherent walking pattern, the depth of penetration between the landing foot and the ground is about 0.01 [m] when landing on the ground. If that were the case, a very large foot contact force occurs, the robot will tip backwards. Therefore, the robot must lift its foot higher than the inherent pattern, that is the $\Delta Z_a(t)$ becomes positive when landing. After the foot lands on the ground and becomes the single-support foot, the robot returns to its planned walking pattern gradually, then the $\Delta Z_a(t)$ becomes zero.



(a) Humanoid walking

(b) Foot position increase

Figure 9: Walking on unknown rough terrain

6 Conclusions

In this paper, we focused on a stable and reliable walking for a biped humanoid. The results of this paper are summarized as follows:

(1) A dual structure of walking control consisting of a feedforward dynamic pattern and a feedback sensory reflex was proposed.

(2) A sensory reflex consisting of a body posture control, an actual ZMP control and a landing time control method was presented.

(3) The effectiveness of our proposed method was confirmed through walks on unknown rough terrain, and in an environment with disturbances by a dynamic simulator and an actual humanoid.

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