Animating Reactive Motions for Biped Locomotion

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ABSTRACT

In this paper, we propose a new method for simulating reactive motions for running or walking human figures. The goal is to generate realistic animations of how humans compensate for large external forces and maintain balance while running or walking. We simulate the reactive motions of adjusting the body configuration and altering footfall locations in response to sudden external disturbance forces on the body. With our proposed method, the user first imports captured motion data of a run or walk cycle to use as the primary motion. While executing the primary motion, an external force is applied to the body. The system automatically calculates a reactive motion for the center of mass and angular momentum around the center of mass using an enhanced version of the linear inverted pendulum model. Finally, the trajectories of the generalized coordinates that realize the precalculated trajectories of the center of mass, zero moment point, and angular momentum are obtained using constrained inverse kinematics. The advantage of our method is that it is possible to calculate reactive motions for bipeds that preserve dynamic balance during locomotion, which was difficult using previous techniques. We demonstrate our results on an application that allows a user to interactively apply external perturbations to a running or walking virtual human model. We expect this technique to be useful for human animations in interactive 3D systems such as games, virtual reality, and potentially even the control of actual biped robots.

Categories and Subject Descriptors

I.3.8 [**Computer Graphics**]: Applications

General Terms

Algorithms

Keywords

motion control,interactive 3D graphics,inverse kinematics

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1. INTRODUCTION

The synthesis of realistic human motion is a challenging research problem with broad applications in movies, special effects, cartoons, virtual reality systems and interactive games. Due to the quality and realism of the result, motion capture data has become a popular and effective means of animating human figures. However, since it is an inherently offline process, there has been great interest in developing algorithms and generative techniques that are suitable for interactive domains. Physically based models of human figures can be used to accurately simulate the dynamics of human motion. However, designing appropriate control schemes can be difficult, and only a limited number of methods consider reactive motions due to the presence of applied external forces [20, 16].

In this paper, we propose a new technique for generating human reactive motion responses to external dynamic perturbations. The key feature of our method is that it can be applied to motions with changing contact states such as walking or running, which are not considered by previous methods. We calculate compensatory motions of the human body that maintain dynamic balance by changing the upper body configuration and stepping out with the foot.

The method proposed in this paper works under the following scenario: First, the user imports some captured motion data to use as a primary motion. At an arbitrary moment, an external peturbation is applied to the body which is modeled as an effective increase in the linear momentum and angular momentum around the center of mass (COM). Our system then automatically calculates a reactive feedback motion for the COM of the body and its angular momentum around the COM by using the Angular Momentum inducing inverted Pendulum Model (AMPM) [8]. The AMPM is an enhanced version of the 3D Linear Inverted Pendulum Mode (3DLIPM) [5], a common method used in robotics to generate motion for biped robots. The AMPM differs from the 3DLIPM in that it can counteract angular momentum induced by external perturbations. Specfically, it allows the explicit modeling of the trajectory of the COM, as well as the angular momentum around the COM. Since a large amount of angular momentum is generated by external perturbations, this feature is essential for generating reactive motions for human figures. Using the AMPM, new trajectories of the COM and the angular momentum are calculated to compensate for the increased angular momentum. By using these trajectories as constraints, the trajectories of the generalized coordinates of the body that satisfy those constraints may be calculated by using constrained inverse kinematics [8].

We also propose a new criterion called the *difference of inertia*, that is based on the difference of the moment of inertia between the current perturbed posture and the corresponding posture in the original (unperturbed) motion. By using the difference of inertia as a criterion, the angular momentum required to bring the current posture back to the original motion can be estimated. As a result, it is possible to calculate motions for human figures that counteract external perturbations, and then gradually converge back towards the original primary motion. We have conducted a number of simulation experiments designed to confirm the behavior and motion generated by the proposed method. We developed a simulated human character that reacts appropriately to various kinds of external perturbations while walking and running. The generated motion appears realistic and compares favorably to actual footage of human reactive compensatory motions. Although we have currently applied the proposed method only to these two examples of biped locomotion, the idea can also be used for non-stepping motions.

The rest of this paper is organized as follows: Section 2 gives an overview of related research, Section 3 gives an overview of the Angular Momentum inducing inverted Pendulum Model, Section 4 and Section 5 describe how to import motion data and calculate compensatory motions, Section 6 presents our experimental results, and Section 7 concludes with a summary discussion.

2. RELATED WORK

Many research has been conducted with the goal of creating, editing, connecting, and retargeting human motion. Due to progress in motion capture technology and improved access to motion capture data, the focus of studies has shifted to utilizing motion data stored in databases. Stochastic methods such as (1) extracting the features of motions and adding them to others [12, 1], (2) connecting different motions in the database to interactively generate a continuous long scene [10, 7], (3) adding new kinematical constraints to the motion, or applying the motion to different characters [3, 11], and (4) editing/creating motion data [13]. All these methods assume that a motion database that contains a large amount of data is available.

Lee *et al.* [10] and Kovar *et al.* [7] enabled interactive character control by searching and connecting motion in the database. They treat human motions as nodes in a graph and search for the motion available in the database that can be used to realize the motion demanded by the user. It is unclear how to utilize these methods to generate reactive motions without resorting to attempting to capture all kinds of reactive motions in advance. Because human balance relies a lot on physical factors, it is important to take into account the dynamics when creating human motion. However, stochastic methods often ignore the dynamics of the motion. It is, therefore, often preferable to synthesize motion by utilizing some physically-based techniques.

There are two main streams of physically based methods in computer graphics. The first set of techniques is based on spacetime constraints [19], which is a method that first specifies a number of keyframe postures, and then interpolates them by minimizing an objective function based on dynamic criteria. Spacetime constraints are very general, but suffer from the cost and difficulty of computing optimizations of nonlinear objective functions, which makes it mostly an offline technique [14]. The computational time and the quality of the final motion heavily depend on the number of parameters and the nature of the objective function. Fang and Pollard [2] have enabled realistic motion in shorter times by removing redundant degrees of freedom from the parameters and skipping the heavy computation of torques and forces. However, the results still cannot be obtained in real-time. Popovic *et al*[17] proposed a method to reduce the number of parameters and succeeded in the generation of various motions such as gait, running, and jumping using spacetime constraints. Since the main concept of spacetime constraints is to generate a motion that minimizes a function throughout the entire motion, it is not suitable to generate reactive feedback for perturbations that are not known in advance.

The other group of techniques is based on forward dynamics. Various motions such as walking gaits [9, 18] and athletic movements such as running, jumping and cycling [4] have been successfully generated by using proportional- derivative (PD) controllers. In PD control, the joint torque is determined by using the target keyframe postures and the elastic and damper parameters:

$$\tau = k_p(\theta - \theta_d) + k_d(\dot{\theta} - \dot{\theta}_d) \quad (1)$$

where τ is the torque applied to the joints, θ is the generalized coordinate value in the current frame, θ_d is the target values of the generalized coordinates, and k_p and k_d are constant parameters that correlate the difference of the current state and the target state to the joint torque that should be applied to the joints. This approach is more suitable for generating reactive motion as the system already includes a feedback model. Previous methods for generating reactive motions [20, 16] actually use this approach. Zordan and Hodgins [20] have proposed a method to generate reactive motion when the virtual human has been punched. Oshita and Makinouchi [16] simulated the motion of a human when heavy luggage was suddenly attached to the back of the body. Although these studies took into account the balance of the body, they did not consider motions with changing contact state such as walking or running, in which the supporting pattern changes periodically. Both of these prevoius methods imported motion capture data as the input, but the feet were constrained to stay fixed to the ground. In order to extend these results to biped locomotion including walking and running, it is necessary to prevent the body from falling and recover the balance while performing the stepping motion. Handling reactive motion during locomotion is more difficult than non-stepping motion because of the added complexity of the changing area of support. In order to maintain balance during biped locomotion, it is necessary to carefully check the trajectory of the zero moment point (ZMP), COM, and angular momentum around the COM.

The balance-preserving methods proposed in the area of robotics can be very effective. When controlling biped robots, the feedforward motion is utilized in order to maintain balance. There are a number of real-time techniques that can compute the trajectories of the ZMP and COM online. The 3D linear inverted pendulum mode (3DLIPM) [5] is one of the technique that is broadly used in robotics to plan stable biped motion. By using the 3DLIPM it is possible to explicitly define the trajectory of the COM and ZMP. As 3DLIPM assumes that no angular momentum around

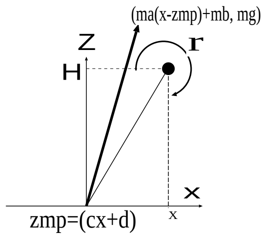

Figure 1: The Angular Momentum inducing inverted Pendulum Model (AMPM). The ZMP is allowed to move over the ground, and its position must be linearly dependent to that of the COM. The horizontal component of the ground force vector is allowed to change, by an amount which must be linearly dependent on the COM.

the COM is generated, angular momentum generated due to noise or external perturbation always needed to be minimized to zero using feedback methods such as the method proposed by Kajita *et al.*[6]. Those work assumes the motion generated remains the same, and the feedback controller seeks to reduce the difference between the current state and the ideal motion. Humans, on the other hand, use a number of different strategies to maintain their balance [15]. For example, when the perturbation is relatively weak, the impact is absorbed by the ankle joint; the posture of the upper part of the body remains unchanged. When the impact is larger, the hip and knee joints are used, and the whole body is used to absorb the impact. If the impact is even stronger, the human will step out one or few more steps to reduce the linear and angular momentum. A number of different strategies are prepared in advance, and the most appropriate motion is launched when the perturbation occurs. This means the balance is kept not only by the feedback controller, but the feedforward motion is also changed according to the current state of the body. Such strategies increase the flexibility and robustness of the human gait. In order to control biped humanoids as humans, a balancing controller that recalculates the upcoming feedforward motion in real-time is needed.

In this paper, we propose a new method to create human reactive motion by taking into account the angular momentum around the COM. The balance-recovery motion is calculated using the AMPM, and the parameters of the AMPM are updated dynamically according to the state of the body after the external perturbation, or dynamic interaction.

3. ANGULAR MOMENTUM INDUCING INVERTED PENDULUM MODEL

In this section, we review the Angular Momentum inducing inverted Pendulum Model (AMPM) [8]. The AMPM enhances the 3DLIPM in the following directions; (1) the ZMP is allowed to move over the ground, (2) the ground force vector is calculated to be not only parallel to the vector connecting the ZMP and the COM; its horizontal element can be linearly correlated to the ZMP-COM vector (Figure 1). As a result, rotational moment will be generated by the ground force. The position of the COM is (x, H), the position of the ZMP is $(cx + d, 0)$, and the vector of the ground force is parallel to the vector $(a(x - zmp) + b, g)$. As the height of the COM is assumed to have a constant value H, the relationship between the acceleration of the COM and its position can be written by:

$$F_x : F_z = \ddot{x} : (\ddot{z} + g) = \frac{H}{g}(a(x - (cx + d)) + b) : H.$$

The differential equation of the COM can then be written by the following form:

$$\ddot{x} = a(1 - c)x + b - ad. \tag{2}$$

The explicit solution for this differential equation can be written as

$$x = -\frac{b - ad}{a(1 - c)} + C_1 e^{-(\sqrt{a-ac})t} + C_2 e^{(\sqrt{a-ac})t} \tag{3}$$

where C_1, C_2 are constant values. As initial parameter values are set as $x = x_0$ and $\dot{x} = v_0$ at $t = 0$, the constant values C_1, C_2 will be as follows:

$$C_1 = \frac{1}{2}(x_0 - \frac{v_0}{\sqrt(a - ac)} + \frac{b - ad}{a(c - 1)}), C_2 = \frac{1}{2}(x_0 + \frac{v_0}{\sqrt(a - ac)} + \frac{b - ad}{a(c - 1)}).$$

Then, the ground force vector can be written as

$$\begin{aligned} F_x &= m\ddot{x} = m(a - ac)\left(C_1 e^{-(\sqrt{a-ac})t} + C_2 e^{(\sqrt{a-ac})t}\right) \\ F_z &= mg \end{aligned}$$

where m is the mass of the system. The rotational moment r around the y-axis can be calculated by

$$r = m(1 - c)(aH - g)\left(C_1 e^{-(\sqrt{a-ac})t} + C_2 e^{(\sqrt{a-ac})t}\right) + mg(\frac{b}{a})$$

and the angular momentum ω_{t_1,t_2} generated by the rotational momentum between times $t = t_1, t_2$ can be obtained as

$$\begin{aligned} \omega_{t_1,t_2} &= [\frac{m(1 - c)(aH - g)}{\sqrt{a - ac}}\left(-C_1 e^{-(\sqrt{a-ac})t} + C_2 e^{(\sqrt{a-ac})t}\right) \\ &\quad + mgt(\frac{b}{a})]_{t_1}^{t_2} + \omega_1 \end{aligned} \tag{4}$$

where ω_1 is the angular momentum at $t = t_1$.

4. IMPORTING THE MOTION DATA

The user needs to specify the original motion before the interaction is applied. For increased realism, we used motion capture data derived from real human motion. If the motion is an artificial motion generated by an artist, the method is still applicable as long as the COM is under the supporting area. A default template human body model with known joint masses and moments of inertia is used. The mass and moments of inertia of each joint segments are then scaled and adjusted to the size of the motion-captured subject. In this study we used a human body model shown in Figure 2 as the default human model. From the motion data, it is possible to calculate the position of the COM by $(\frac{\sum_i m_i \boldsymbol{x_i}}{\sum_i m_i}, \frac{\sum_i m_i \boldsymbol{y_i}}{\sum_i m_i}, \frac{\sum_i m_i \boldsymbol{z_i}}{\sum_i m_i})$, where m_i, x_i, y_i, z_i represents the mass and position of segment i. The position of the ZMP can be calculated by

$$\boldsymbol{zmp_x} = \frac{\sum_i m_i x_i(\ddot{z}_i - g) - \sum_i m_i z_i \ddot{x}_i}{\sum_i m_i(\ddot{z}_i - g)}$$
$$\boldsymbol{zmp_y} = \frac{\sum_i m_i y_i(\ddot{z}_i - g) - \sum_i m_i z_i \ddot{y}_i}{\sum_i m_i(\ddot{z}_i - g)}.$$

Because the trajectory of the ZMP is very sensitive to noise, the trajectories of (x_i, y_i, z_i) are first smoothed by a medium filter. Then, the trajectory of the COM and ZMP will be

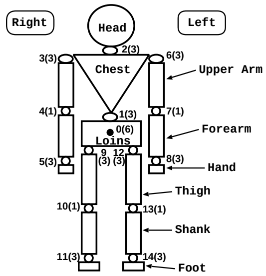

Figure 2: The human body model used in the simulation.

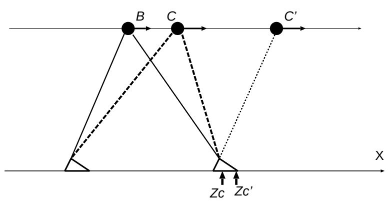

Figure 3: Calculating the AMPM parameters for walking in the sagittal plane. The initial position of the ZMP of the landing foot is adjusted so that the position and velocity of the COM at the end of the single support phase closely matches the imported data.

approximated by the AMPM. Note that the COM and ZMP calculated by the AMPM will not completely match the trajectories of the COM and the ZMP in the original data, since the AMPM is only a simplified model and cannot fully describe the complexity of real human motion precisely. However, the horizontal trajectory of the COM of the human body can be approximated by the AMPM as long as the height of the COM does not change dramatically.

Since the amount of angular momentum around the COM during biped locomotion is quite limited, the AMPM parameters are estimated assuming that no angular momentum is generated during the motion. Both the single support phase and the double support phase is represented by separate sets of AMPM parameters. It is first necessary to estimate the time and the topology of the support switching using the trajectories of the ZMP and the location of the footsteps on the ground.

Because the AMPM handles the motion in the sagittal plane and frontal plane independently, different sets of AMPM parameters are needed for the motion in each plane. For independent steps, different local coordinate systems that determine the sagittal and frontal plane are defined. Then, the AMPM parameters that can reproduce similar trajectories of the COM are estimated from the captured motion. The parameters for the sagittal plane are estimated, and then the parameters for the frontal plane are calculated.

In the case of walking, every double support phase and single support phase is represented by a single set of AMPM parameters. To explain the idea, let us assume the situation shown in Figure 3. The position of the COM for the AMPM model at the beginning and ending of double support phases are represented by points B and C, and the ending point of the following single support phase is represented by point C'. The corresponding positions of the COM in the original imported motion are defined here by B^o, C^o and C'^o.

In order to reduce the difference of the position and velocity of the COM between the AMPM model and the original motion at point C', the positions of the ZMP of the AMPM model at points C and C', denoted here by Z_c and $Z_{c'}$, are adjusted. The position and velocity of the COM of the AMPM model at points B, C, and C' are defined by $x_B, x_c, x_{c'}$ and $v_B, v_c, v_{c'}$ respectively. As the angular momentum produced during walking and running is limited, it is assumed that the ground force vector whose origin is at the ZMP always passes through the COM. As a result, the relationship of the acceleration and position of the COM between points B, C and C' can be written by

$$\ddot{x} = \frac{g}{H}(x - zmp_x).$$

where x and $\ddot{x}$ are the position and acceleration of the COM in the sagittal plane, and zmp_x is the position of the ZMP in the sagittal plane. Since we assume that the ZMP moves over the ground proportionally to the COM as

$$zmp_x = cx + d,$$

Equation 5 can be rewritten by

$$\ddot{x} = \frac{g}{H}(x - cx - d).$$

At points B, C and C', the following constraints must be satisfied:

$$\ddot{x_b} = \frac{g}{H}(x_b - z_b), \ddot{x_c} = \frac{g}{H}(x_c - z_c), \ddot{x_{c'}} = \frac{g}{H}(x_{c'} - z_{c'}).$$

As a result, the trajectory of the COM can be obtained by using Equation 3. The position and velocity of the COM at the points corresponding to B, C and C' in the original human motion are defined by $x^o_B, x^o_c, x^o_{c'}$ and $v^o_B, v^o_c, v^o_{c'}$. The error measure $f^{c'}$ to be minimized is

$$f^{c'} = (x_c - x^o_c)^2 + (v^o_{c'} - v_{c'})^2. \quad (5)$$

The values of $x_{c'}$ and $v_{c'}$ depend on z_c and $z_{c'}$. In order to minimize $f^{c'}$, the positions of z_c and $z_{c'}$ must be adjusted. Because the distance between the two points are assumed to be constant (the size of the foot is constant), minimizing $f^{c'}$ becomes an optimization problem with a single parameter, z_c. The solution for this problem can be found by using the golden search method. For each combination of the double support phase and the single support phase, the above method is applied both in the sagittal plane and in the frontal plane. Applying this method to the AMPM, it is possible to obtain the trajectory of the COM that moves as close as possible to the COM trajectory of the original data.

Running motion differs from the walking motion in that there is no double support phase preceding the single support phase. Instead, the trajectory of the COM follows Newton's laws of dynamics while the body is airborne. During the single support phase, similar to the walking motion, the horizontal trajectory is also represented by the AMPM. Moreover, the position of the landing foot is adjusted so that f^c is minimized at the end of the single support phase.

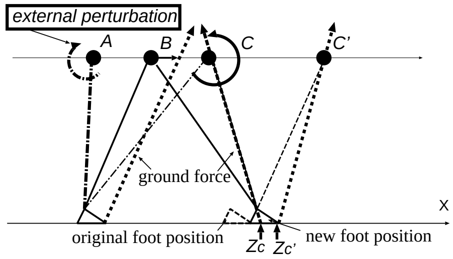

Figure 4: The gait motion pattern in the sagittal plane. The external perturbation is applied during the single support phase, when the COM is at point A. The positions of the COM when the double support, single support, and the next double support phase start are defined by point B, C, and C'.

5. USING THE AMPM TO COUNTERACT EXTERNAL PERTURBATIONS IN THE SAGITTAL PLANE

Suppose the motion of the humanoid in the sagittal plane is defined as shown in Figure 4. As previously explained, it is assumed that the ground force vector always passes through the COM in the original motion. The human figure is originally in the single support phase, and an external perturbation is applied to the humanoid body causing a sudden increase in the linear and angular momentum when the COM is at point A. The increased linear momentum can be reduced by using the existing approach of the 3DLIPM. However, it was difficult to reduce the induced angular momentum, especially when the amount is large.

The increase in the linear and angular momentum are defined here by ΔL and ΔM. Even after the perturbation, we assume that the height of the center of gravity remains unchanged, and that the vertical velocity of the center of gravity is zero. Actually, it is possible to summarize all of the effects of the external perturbation as an increase in the horizontal component of the linear momentum and the angular momentum, by forcing the COM to stay at the same height using a conventional feedback algorithm such as PD control. However, this would further increase the angular momentum of the body around the center of gravity. After the perturbation, the COM will move along the horizontal axis; the angular momentum will stay at the same value during the single support phase, and it will be reduced during the following double support phase. The following two strategies are used for this purpose:

- the position of the swing leg landing onto the ground will be modified
- rotational momentum will be applied to the body during the double support phase to counteract the angular momentum induced by the external perturbation.

For the motion during the double support phase, it is assumed that the coordinate values of point B and C in Figure 4, which are the points of the COM when the double support phase begins and ends, will be the same as those in the original gait motion. The motion of the COM and the trajectory of the angular momentum will be governed by the AMPM during the double support phase. The ground force vector will be parallel to the vector connecting the ZMP and COM at point C. The acceleration of the COM will be discontinuous at point B, as the ground force vector will be adjusted so that the angular momentum will be reduced to zero when the COM arrives at C. Let us assume the the position of the next foot is decided and the coordinate value of the ZMP at point C and C' are defined by z_c and z'_c. The new differential equation of the COM during the double support phase is defined here by

$$\ddot{x} = px + q \qquad (6)$$

where p and q are the parameters to be calculated. The constraint that the increased angular momentum will be reduced to zero can be written in the following form:

$$\omega_{B,C}(p, q) = \Delta M \qquad (7)$$

where $\omega_{B,C}(p, q)$ is the angular momentum generated during the double support phase and it can be explicitly written by using Equation 4. As the ground force vector is parallel to the vector connecting the ZMP and COM at point C, the following equation must be satisfied:

$$\frac{g}{H} x_c = px_c + q \qquad (8)$$

where x_c is the coordinate value of the COM at point C and H is the height of the COM.

By substituting Equation 8 into Equation 7, it becomes a constraint with only one parameter:

$$\omega_{B,C}(p) = \Delta M. \qquad (9)$$

Unfortunately, there is no explicit solution for p in Equation 9. Although the solution must be calculated numerically, because the relationship between p and $\omega_{B,C}(p)$ is monotonic around the solution, a high-precision solution can be obtained with only a small number of iterations.

The increased linear momentum ΔL must also be reduced to zero. In order to do this, the method proposed by Kajita *et al*[5] is used, which is to minimize the following function:

$$(x_{c'} - x^O_{c'})^2 + (v_{c'} - v^O_{c'})^2 \qquad (10)$$

where $x_{c'}$ and $v_{c'}$ are the position and velocity of the COM at point C' and $x^0_{c'}$ and $v^0_{c'}$ are the corresponding values in the original feedforward motion. The reduction of the linear momentum is considered only after the angular momentum has been reduced enough, because the angular momentum is more critical for stability.

To summarize, the motion in the frontal plane is calculated by searching for the foot-landing position that minimizes Equation 10. The motion during the double support phase is determined by solving for p using Equation 9.

5.1 Difference of Inertia

Although the angular momentum can be reduced to zero by adjusting the AMPM parameters, the posture of the body will be different from the original gait, unless angular momentum is generated to bring the body to the original posture. In order to solve this problem, we introduce a new criterion called the *difference of inertia*, that can be used to estimate the amount of additional angular momentum that must be added to the body to bring it back to the original posture calculated by the feedforward controller. The difference of inertia can be defined as follows:

$$\Delta I = \sum_i (c_i - c_g) \times (c_i - c^o_i) + R_i I_i R_i^T (\theta^o_i - \theta_i) \qquad (11)$$

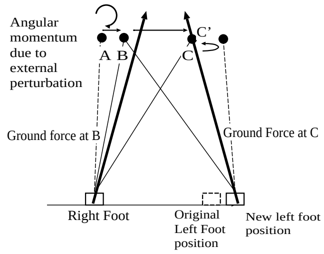

Figure 5: Counteracting the angular momentum induced by an external perturbation in the frontal plane. The external perturbation is applied during the single support phase at point A. The foot landing position on the ground is modified, resulting in a different ground reaction force vector at point C.

where c_i is the position of COM, c_i^o is the COM in the original motion, θ_i is the orientation, θ_i^o is the orientation in the original motion, R_i is the 3×3 rotational matrix, I_i is the moment of inertia of segment i, respectively, and c_g is the COM of the whole body. By dividing the difference of inertia by the transition interval, it is possible to calculate the angular momentum needed to bring the posture to the target posture. In order to recover the original motion inertia during the double support phase, an angular momentum of value $\Delta I/\widetilde{T_{B,C}}$ must be added to the body, where $\widetilde{T_{B,C}}$ is the estimated duration of the double support phase that can be calculated by dividing the distance between B and C by the velocity of the COM at point B:

$$\widetilde{T_{B,C}} = \frac{x_C - x_B}{v_B}$$

where x_B, v_B, and x_C are the position and velocity of the COM at point B, and the position of point C, as well.

Instead of solving Equation 9, the following equation can be used to calculate the motion to recover the original posture:

$$\omega_{B,C}(p) = \Delta M + \beta \frac{\Delta I}{\widetilde{T_{B,C}}} \quad (12)$$

where β is a weight value smaller than 1, a necessary condition for stable convergence.

For each of the subsequent walking steps, the motion for the next double support phase is recalculated using the error of the linear and angular momentum at the end of the previous double support phase, by solving Equation 12. As a result, the motion gradually converges back to the original motion after a few steps.

5.2 Using the AMPM to counteract external perturbation in the frontal plane

The motion of the COM in the frontal plane can be explained by the AMPM as shown in Figure 5. During the double support phase, the ZMP will move proportionally to the COM, and during the single support phase, the ZMP will stay at the same position under the supporting foot. If we assume that no angular momentum is generated, the vector connecting the COM and the ZMP will always be parallel to the ground reaction force.

To clarify the idea of the feedback approach in this study, again let us assume that the ground reaction force vector is always parallel to the vector connecting the COM and the ZMP in the original feedforward motion. An external perturbation is applied to the body at point A, during the single support phase, as shown in Figure 5. As a result, angular momentum of an amount ΔM^f is induced around the frontal axis. In order to reduce this angular momentum to zero, the motion in the double support phase and the next single support phase will be modified. As before, the strategies used for the motion in the sagittal plane will be used: (1) the position of the swing leg landing onto the ground will be changed (2) rotational momentum will be applied to the body during the double support phase to counteract the angular momentum induced by the external perturbation.

The new differential equation of the COM during the double support phase is defined by

$$\ddot{y} = p_y y + q_y \quad (13)$$

where p_y, q_y are the AMPM parameters. Because the duration of the double support phase, $T_{B,C}$ is determined by the motion in the sagittal plane, the position and velocity at point C can be obtained by

$$\begin{aligned} y_C &= \frac{\sqrt{p_y}(y_B + \frac{q_y}{p_y} - \dot{y}_B)}{2} e^{-\sqrt{p_y}T_{B,C}} \\ &+ \frac{\sqrt{p_y}(y_B + \frac{q_y}{p_y} + \dot{y}_B)}{2} e^{\sqrt{p_y}T_{B,C}} - \frac{q_y}{p_y} \\ \dot{y_C} &= -\frac{p_y(y_B + \frac{p_y}{q_y} - \dot{y_B})}{2} e^{-\sqrt{p_y}T_{B,C}} \\ &+ \frac{p_y(y_0 + \frac{q_y}{p_y} + \dot{y_B})}{2} e^{\sqrt{p_y}T_{B,C}}. \end{aligned}$$

where $y_B, y_C, \dot{y_B}, \dot{y_C}$ are the positions and velocities of COM at point B and point C, respectively. The calculation is similar to the case for the motion in the sagittal plane. To calculate p_y and q_y, the following two constraints are taken into account:

$$\omega_d = -\Delta M^f + \beta_y \frac{\Delta I^f}{\widetilde{T_{B,C}}} \quad (14)$$

$$\frac{y_c - z_c^f}{H} g = p_y y_c + q_y \quad (15)$$

where ΔI^f is the difference of inertia at point B, and β_y is a constant value smaller than 1 to ensure the convergence of the method.

For z_c^f, the position of the foot landing onto the ground, a value that minimizes the following mean square error function is adopted:

$$(y_{c'} - y_{c'}^O)^2 + (\dot{y}_{c'} - \dot{y}_{c'}^O)^2 \quad (16)$$

where $y_{c'}$ and $\dot{y}_{c'}$ are the position and velocity of the COM at point C' and $y_{c'}^0$ and $\dot{y^0}_{c'}$ are the corresponding values in the original feedforward motion.

To summarize, the motion in the frontal plane is calculated by searching for the foot-landing position that minimizes Equation 16. The motion during the double support phase is determined by calculating the AMPM parameters p_y and q_y by using Equations 14 and 15 as constraints.

5.3 Calculating the generalized coordinates using inverse kinematics

As we have already defined the trajectories of the COM and the angular momentum, the next step is to calculate kinematic parameters that satisfy these constraints. Constrained inverse kinematics is used for this purpose. The human body model shown in Figure 2 was used. A translational degree of freedom was added to the knee to avoid the singularity ath this joint. Trajectories of generalized coordinates of the human body model are defined here as $\boldsymbol{q}(t) = (q_1(t), q_2(t), ..., q_{\mathrm{dof}}(t))^T$ where dof is the number of degrees of freedom of the human body model, and the value is forty. Generalized coordinates $\boldsymbol{q}(t)$ include the position and rotation of the root of the body in the 3D world coordinate system.

The relationship between velocity of the COM and velocity of the generalized coordinates can be written as follows:

$$\dot{\boldsymbol{x}}_g = J_{\mathrm{com}}\,\dot{\boldsymbol{q}},$$

where J_{com} is the Jacobian matrix that consists of the partial derivatives of the COM by the generalized coordinates. Then, the acceleration of the COM can be derived as follows:

$$\ddot{\boldsymbol{x}}_g = J_{\mathrm{com}}\,\ddot{\boldsymbol{q}} + \dot{J}_{\mathrm{com}}\,\dot{\boldsymbol{q}}. \quad (17)$$

The angular momentum $\boldsymbol{r}$ and the first derivative of the generalized coordinates have a linear correlation:

$$\boldsymbol{r} = R\dot{\boldsymbol{q}}.$$

The derivative of the angular momentum can be derived as follows:

$$\dot{\boldsymbol{r}} = R\ddot{\boldsymbol{q}} + \dot{R}\dot{\boldsymbol{q}}. \quad (18)$$

The translational and rotational acceleration of the feet can be expressed as functions of $\ddot{\boldsymbol{q}}$ as well:

$$(\ddot{\boldsymbol{p}}_l, \ddot{\boldsymbol{p}}_r, \ddot{\boldsymbol{\theta}}_l, \ddot{\boldsymbol{\theta}}_r)^T = J_f\ddot{\boldsymbol{q}} + \dot{J}_f\dot{\boldsymbol{q}}. \quad (19)$$

The trajectories of the feet are calculated by scaling the trajectories of the original feet using the subsequent positions of the foot steps;

$$(p_x, p_y) = \left(\frac{s_x^{i+1} - s_x^i}{s_{x,0}^{i+1} - s_{x,0}^i}(p_x^0 - s_x^i) + s_x^i,\ \frac{s_y^{i+1} - s_y^i}{s_{y,0}^{i+1} - s_{y,0}^i}(p_y^0 - s_y^i) + s_y^i\right)$$

where (s_x^i, s_y^i) and (s_x^{i+1}, s_y^{i+1}) are the position of the ith and $(i+1)$th footsteps on the floor in the newly generated motion, $(s_{x,0}^i, s_{y,0}^i)$ and $(s_{x,0}^{i+1}, s_{y,0}^{i+1})$ are the corresponding positions of the footsteps in the original motion, and (p_x, p_y) is the position of the foot in the horizontal plane in the newly generated motion, and (p_x^0, p_y^0) is the corresponding position in the original motion.

The rotation of the feet in the new motion will be calculated by using the step length as a scaling factor: $\theta_y = (s_l/s_l^0)\theta_y^0$. This is due to the fact that the orientation of the feet enlarges as the step length gets larger.

Combining Equation 17, 18, and 19, linear constraints that must be satisfied by the body can be summarized to the following form:

$$\boldsymbol{\lambda} = J_{\mathrm{all}}\,\ddot{\boldsymbol{q}} + \dot{J}_{\mathrm{all}}\,\dot{\boldsymbol{q}}. \quad (20)$$

where $\boldsymbol{\lambda} = (\ddot{\boldsymbol{x}}_g, \dot{\boldsymbol{r}}, \ddot{\boldsymbol{p}}_l, \ddot{\boldsymbol{\theta}}_l, \ddot{\boldsymbol{p}}_r, \ddot{\boldsymbol{\theta}}_r)^T$, and $J_{\mathrm{all}} = (J_{\mathrm{com}}, R, J_f)^T$. Calculating $\ddot{\boldsymbol{q}}$ that satisfies Equation 20 can be considered as a constrained inverse kinematics problem.

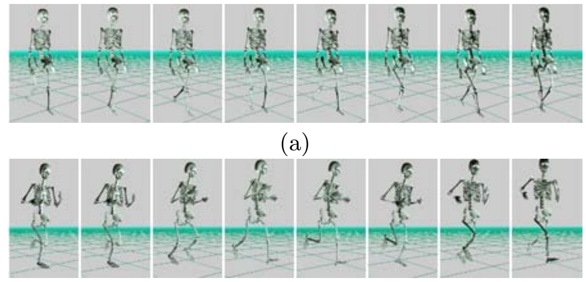

Figure 6: The original (a) walking and (b) running motion

Since the goal is to calculate a stable gait motion, the following quadratic form is minimized with respect to $\ddot{\boldsymbol{q}}$:

$$(\ddot{\boldsymbol{q}} - k(\boldsymbol{q} - \boldsymbol{q}_0) + d\cdot\dot{\boldsymbol{q}})(\ddot{\boldsymbol{q}} - k(\boldsymbol{q} - \boldsymbol{q}_0) + d\cdot\dot{\boldsymbol{q}})^T. \quad (21)$$

where k, d are the elastic and damping constants, respectively. Quadratic programming is used to calculate $\ddot{\boldsymbol{q}}$ by minimizing Equation 21 subject to the constraint given by Equation 20.

Using the calculated acceleration, the values of the generalized coordinates and their velocity were updated step by step, and finally, the whole trajectory was obtained.

6. EXPERIMENTAL RESULTS

To show the performance of the proposed method, two biped locomotions including walking and running were used for experiments. The original motions are shown in Figure 6. After loading the motion, external perturbations, in the form of balls colliding with the body were simulated. The external perturbations are added interactively by the user specifying from which direction the ball should collide to which part of the body. The mass of the ball can also be changed, which affects the the amount of impact force produced during the collision. Balls coming from the front reduced the velocity of the COM and generated angular momentum that caused the body to rotate backward. Balls colliding from behind increased the velocity of the COM, and generated angular momentum that caused the body to rotate forward. An experiment was first done to compare the motions generated with our system and real human motions. During walking and running motions, external perturbations were applied to the human body from behind. Two levels of strength were tested; a weak impact and a strong impact. The results are shown in Figure 7 (a) and (b). When the impact was small, the resulting posture had less distortion, and after a few steps the motion would gradually return to the original one as shown in Figure 7 (a). When strong impact was applied, the chest was fully bent, the shoulder joints were extended backward, and the knees were also extended during the balance keeping motion as shown in Figure 7 (b). Comparing the simulated results with real human motions, similar phenomena could be observed. Additional experiments were conducted for the running motion. The motion when setting β in Equation 12 to 0.3 resembled the real human motion best, as shown in Figure 7 (c).

For the running motion, by changing the parameter of β, it was possible to generate different reactive motions; when β was set to 0.7, the human body model quickly raised the

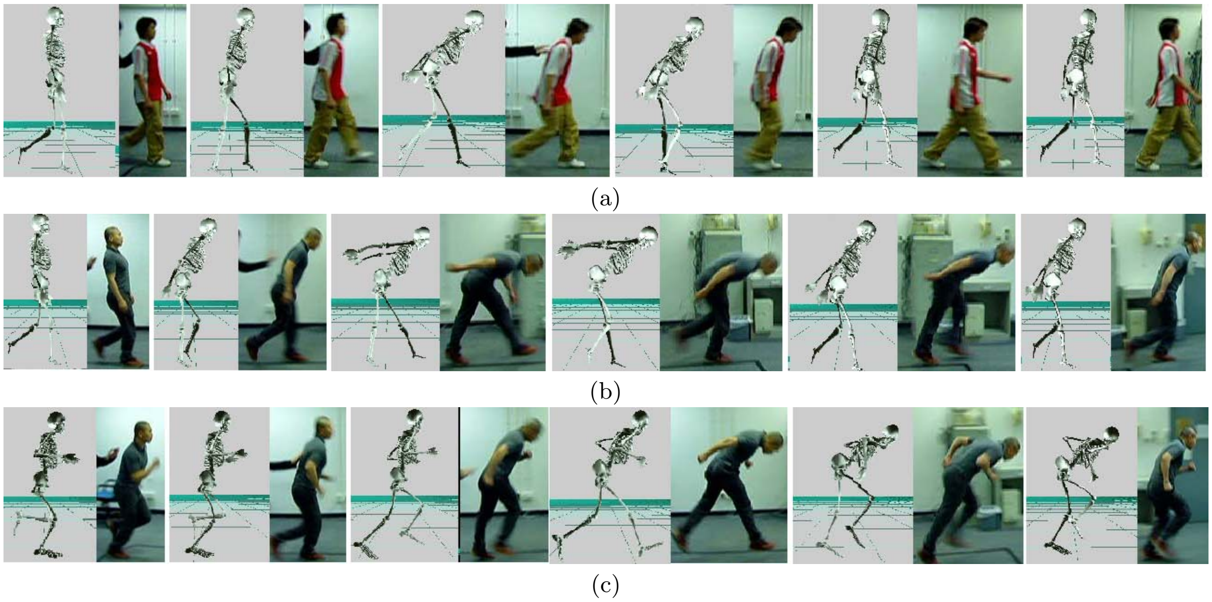

Figure 7: Comparison of real human motion and simulated motion generated using the method presented; (a) the reactive motion during walking when the external perturbation is weak, (b) the motion when it is strong, and (c) the reactive motion during running by setting $\beta = 0.3$ in Equation 12.

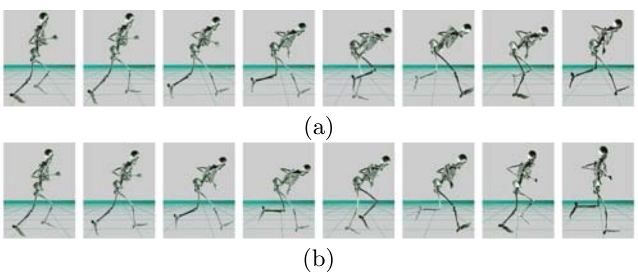

Figure 8: Comparison of the reactive motion during running by setting β in Equation 12 to (a) 0.3 and to (b) 0.7.

chest in the following step, whereas when it was set to 0.3, the human body model continued to run a few steps while keeping the chest bent. The reactive motion also involves the musculoskeletal model of the human body, and there is a limitation in the amount of force that can be exerted by the legs. Such limitations are not implemented yet in these results, and therefore, it is possible for the body to encounter a large amount of torque that is actually not physically exertable by the body. In order to find out the most appropriate value for β, it will be necessary to take into account the limitation of the musculoskeletal model.

Finally, using our interactive system, many balls were thrown at human body model from various directions as shown in Figure 9, causing a variety of different body postures disturbances. The simulated human model was still able to recover its balance.

7. SUMMARY AND DISCUSSION

In this paper, we proposed a new method to generate human reactive motion when dynamic interaction is applied to the body during biped locomotion including walking and running. Using our method, it is possible to simulate the motions that the human body uses to dynamically maintain balance by altering the body configuration and changing the position of the stepping foot.

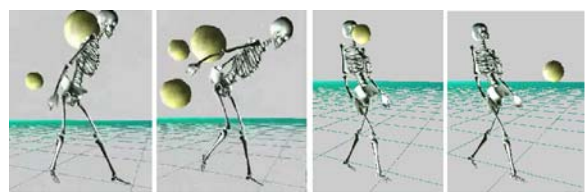

Figure 9: Interactively creating reactive motions of the body by simulated impacts due to balls thrown from various directions.

One of the advantages of our method is its simplicity: the user can just import some motion capture data, apply arbitrary forces to the body, and the reactive motion is generated automatically. No additional motion data is needed for the calculation of the reactive motion. As the gait motion is much more unstable during the single support phase than during the double support phase, we applied external perturbations only during the single support phase. However the algorithm can also be applied to situations involving external perturbations applied to the body during the double support phase, or even when the body is airborne during running. In our experiments, the simulated motion compared favorably to actual footage of real humans encountering external forces. Although we were satisfied with the generated motion, there are a number of ways in which our current method could be improved, which forms the basis of our future work.

We adopted an approach that is commonly used in biped robot control: first calculating the trajectory of the COM, ZMP and angular momentum, and then obtaining the generalized coordinates. When calculating the reactive motion during biped locomotion, keeping the balance of the body becomes a very critical issue. When using methods based on PD control, it is difficult to predict the motion of the COM and ZMP as the acceleration of the body will be determined based on the difference of the current state and the target motion. In this study, the trajectories of the the COM, ZMP and angular momentum that satisfy simplified dynamics are first calculated explicitly using the AMPM. Then, the values of the generalized coordinates that satisfy the trajectories are obtained using constrained inverse kinematics. The balance of the body is considered as a constraint on the motion, so it is possible to maintain balance despite the external perturbations. However, there will clearly be some upper bound on the magnitude of the disturbance that can be stably compensated for, which will depend on a reasonalbe model of joint torque limits.

Some limitations of the current approach can be considered as follows: First, we have assumed that the angular momentum in the original motion is small enough to be negligible in the original motion. Although this assumption is acceptable for motion such as walking and running, it is not acceptable for motions such as somersaults or acrobatic motions. In order to handle such cases, it is necessary to find the AMPM parameters that can approximate the angular momentum generated in those motions. Importing such motion to this reactive system is one of our current research topics.

Second, the constrained inverse kinematics implementation we used is computationally costly and therefore, it is not possible to generate animation in real-time at this moment. The frame rate for the online animation takes about 0.5 second per frame using a Pentium IV 2GHz CPU, which is not yet fast enough for interactive animation. Better hardware and an improved, optimized implementation will likely overcome this limitation in the future.

Thirdly, the user has a limited number of options for generating the reactive motion. Since this study assumes that the input is only a single motion, the user can only change the parameters such as the weight matrix for the inverse kinematics, or the weight of the difference of inertia for recovering the balance in Equation 15. It is difficult to create various types of reactive motion just by changing such parameters. One way to deal with such demands is to prepare a number of reactive motions for some part of the body, for example the arms, and switch on such motions when external perturbation occurs. It is possible to calculate the motion of the remaining parameters such that the trajectories of the COM and ZMP, and the angular momentum of the body match with those calculated by the AMPM.

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