A Feedback Controller for Biped Humanoids that Can Counteract Large Perturbations During Gait

Taku Komura
City University of Hong Kong
taku@ieee.org

Abstract

In this paper, we propose a new method for biped humanoids to compensate a large amount of angular momentum induced by strong external perturbations applied to the body during gait motion. Such angular momentum can easily cause the humanoid to fall down onto the ground. We use the enhanced version of 3D linear inverted pendulum mode named Angular Momentum inducing inverted Pendulum Model (AMPM) to calculate the motion. As AMPM allows users to explicitly calculate the angular momentum generated by the ground reaction force, it is possible to calculate the counteracting motion that compensates the angular momentum generated by the external perturbation in real-time.

1 Introduction

Biped locomotion of humanoid robots is one of the most exciting topics these days. Many researchers have proposed feedforward algorithms to let humanoid robots walk. [5, 2, 1, 4]. The trajectories generated by these motion planners are dynamically feasible motions; that means the trajectory of the Zero Moment Point always move within the convex hull surrounded by the supporting area.

As gait motion by bipeds are quite unstable, in order to achieve stable gait, a feedback controller must be used. Kajita et al.[6] calculated the additional rotational momentum that must be applied to the body to keep the balance by using the angular momentum as a direct reference. Napoleon et al.[8] proposed a feedback method based on a two link inverted pendulum model. In these researches, the motion generated by the motion planner are kept the same, and the feedback controller tries to reduce the difference of the current status and the ideal motion.

The feedback controller was used to simulate stable standing motion and kicking motion.

Humans, on the other hand, use different strategies to keep their balance. according to the amount of force applied to the body. 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 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 status of the body. Such strategies increases the flexibility and robustness of the human gait. In order to control biped humanoids as humans, a balancing controller that retune the upcoming balancing motion in real-time is needed.

In this paper, we propose a new feedback method for biped humanoids to counteract strong external perturbation using the Angular Momentum inducing inverted Pendulum Model (AMPM), which is an enhanced version of the 3D Linear Inverted Pendulum Mode (3DLIPM). Using AMPM, it is possible to explicitly calculate angular momentum generated during the motion. After the perturbation, new trajectories of the COG 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 including the position of the center of the loins and the joint angles that satisfy those constraints are calculated by using inverse kinematics, as done in [7, 3].

We also propose a new criteria called the *distortion of inertia*, that is based on the difference of the moment of inertia between the current posture and the corresponding posture in the original motion. By using the distortion of inertia as a criteria, the angular momentum needed to bring the posture back to the original motion can be estimated. As a result, it is possible to calculate the motion of the humanoid which counteracts the external perturbation, and then gradually moves back to the original gait motion. A number of experiments were conducted to check the validity of the proposed method. After applying various kinds of perturbation to the humanoid during gait motion, the counteracting motion could be properly calculated. Although we have applied the proposed method only to gait motion, the idea can be used for motions such as running and standing, as well.

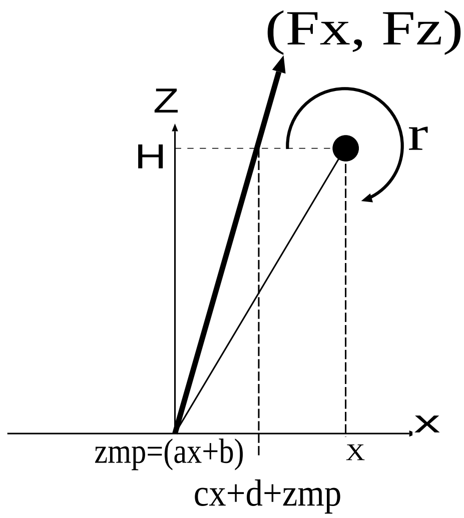

Figure 1: The Angular Momentum inducing inverted Pendulum Model (AMPM). The ZMP is allowed to move over the ground, and its position must be linearly dependent to that of the COG. The horizontal component of the ground force vector is allowed to change, by an amount which must be linearly dependent on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

2 Angular Momentum inducing inverted Pendulum Model

In this section, we review the Angular Momentum inducing inverted Pendulum Model (AMPM) [7]. The AMPM enhances 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 COG; its horizontal element can be linearly correlated to the ZMP-COG vector (Figure 1). As a result, rotational moment will be generated by the ground force. The position of the COG is (x, H), the position of the ZMP is $(ax + b, 0)$. and the normal vector of the ground force is parallel to vector $(cx + d, H)$. The relationship between the acceleration of the COG and its position becomes:

$$F_x : F_y = \ddot{x} : (\ddot{z} + g) = (cx + d) : H.$$

As the height of the COG is $z = H$, we can write

$$\ddot{x} = \frac{g}{H}(cx + d). \tag{1}$$

The solution for this differential equation can be written as

$$x = C_1 e^{-\frac{t}{T_e}} + C_2 e^{\frac{t}{T_e}} - \frac{d}{c}$$

where $T_e = \sqrt{H/(cg)}$, and C_1, C_2 are constant values. As initial parameter values are set at $x = x_0$ and $\dot{x} = v_0$ at $t = 0$, the constant values C_1, C_2 are

$$C_1 = \frac{x_0 + \frac{d}{c} - v_0 T_e}{2}, \quad C_2 = \frac{x_0 + \frac{d}{c} + v_0 T_e}{2}.$$

Then, the ground force vector can be written as

$$\begin{aligned} F_x &= m\ddot{x} = \frac{m}{T_e^2}\left(C_1 e^{-\frac{t}{T_e}} + C_2 e^{\frac{t}{T_e}}\right) \\ F_z &= mg \end{aligned}$$

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

$$\begin{aligned} r &= -\frac{mH}{T_e^2}\left(C_1 e^{-\frac{t}{T_e}} + C_2 e^{\frac{t}{T_e}}\right) \\ &\quad -mg\left((a-1)\left(C_1 e^{-\frac{t}{T_e}} + C_2 e^{\frac{t}{T_e}} + \frac{d}{c}\right) + b\right) \end{aligned}$$

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

$$\omega_{t_1,t_2} = m\left[\left(-C_1 e^{-\frac{t}{T_e}} + C_2 e^{\frac{t}{T_e}}\right)\left(-\frac{H}{T_e} - gT_e(a-1)\right) - g\left((a-1)\frac{d}{c} + b\right)t\right]_{t_1}^{t_2} + \omega_1 \quad (2)$$

where ω_1 is the angular momentum at $t = t_1$. In the following sections, we show how this enhanced IPM can be used to generate COG trajectories in the frontal and lateral plane.

2.1 Using the AMPM to counteract external perturbation in the sagittal plane

Suppose the motion of the humanoid in sagittal plane is defined as shown in Figure 2. To clarify the concept of our approach, let us assume here that no angular momentum around the COG is generated in the original feedforward motion. That means the ground force vector always passes through the COG. Let us assume the humanoid is first in single support phase, and external perturbation was applied to the humanoid body causing sudden increase in the linear and angular momentum when the COG is at Point A. The increased linear momentum can be reduced by using existing approaches of 3DLIPM. However, it was difficult to reduce the induced angular momentum by previous approaches especially when the amount is large.

The increase in the linear and angular momentum are defined here by ΔL and ΔM, as well. Even after the perturbation, we assume the height of the center of gravity is same as before, and the vertical velocity of the center of gravity is

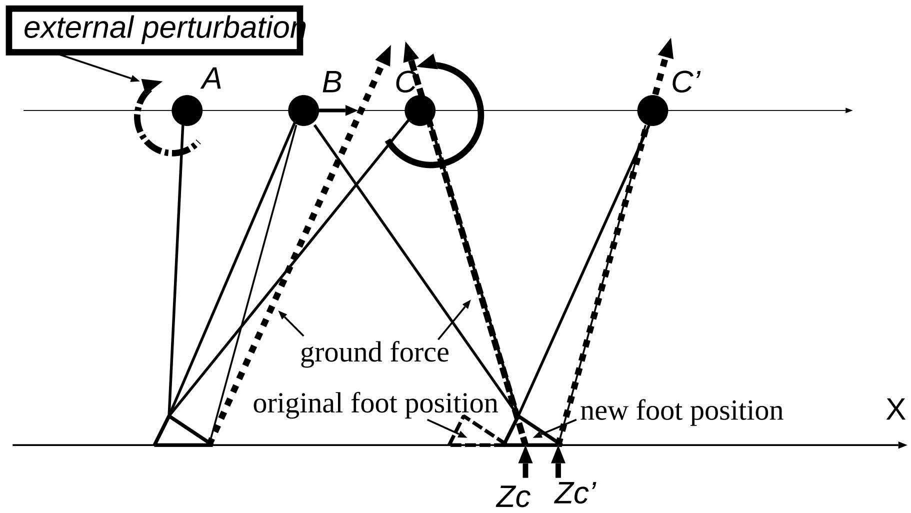

Figure 2: The gait motion pattern in the sagittal plane. The external perturbation is applied during single support phase, when the COG is at Point A. The positions of the COG when the following double support, single support, and double support phase start are defined here by Point B, C, and C', as well. The angular momentum generated by the external perturbation is compensated mainly between Point B and C'.

zero as well. Actually, it is possible to summarize all the effect of the external perturbation to the increase in the horizontal component of of the linear momentum and the angular momentum, by forcing the COG to stay at the same height using conventional feedback algorithm such as PD control, although this would further increase the angular momentum of the body around the center of gravity. After the perturbation, the COG will move along the horizontal axis, and the ground force vector will penetrate the COG as same as in the original motion. Therefore, the angular momentum will stay at the same value during the single support phase. In order to reduce the increased linear and angular momentum to zero, the motion during the following double support phase and the single support phase will be modified. The following two strategies are used for this purpose:

- the position 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 double support phase, the following two assumptions are made: (1) the coordinate values of Point B and C in Figure 2, which are the points of COG when the double support phase begins and ends, as well, will be the same as those in the original gait motion, and (2) increased angular momentum will be compensated during the double support phase. The motion of the COG and the trajectory of the angular momentum will follow the rule of AMPM during the double support phase. The ground force vector will be parallel to the vector connecting the ZMP and COG at Point C. The acceleration of the COG will be uncontiunous at Point B, as the ground force vector will be adjusted so that the angular momentum will be reduced to zero when the COG arrives to C. Let us assume the position of the new foot position is decided and the coordinate value of the ZMP at Point C and C' are defined by z_c and z'_c, as well. The new differential equation of the COG during the double support phase is defined here by

$$\ddot{x} = px + q \tag{3}$$

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

$$\omega_{B,C} = \Delta M \tag{4}$$

where $\omega_{B,C}$ is the angular momentum generated during double support which can be explicitly written by the form in Equation 2. As the ground force vector is parallel to the vector connecting the ZMP and COG at Point C, the following equation must be satisfied:

$$\frac{g}{H}x_c = px_c + q \tag{5}$$

where x_c is the coordinate value of the COG at Point C and H is the height of the COG.

By substituting Equation 5 into 4, the following equation can be obtained:

$$\omega_{B,C}(p) = \Delta M \tag{6}$$

where $\omega_{B,C}(p)$ is a function that returns the angular momentum generated between Point B and Point C using p as an input. Unfortunately, there is no explicit solution for p in Equation 6. Although the solution must be calculated numerically, as the relationship between p and $\omega_{B,C}(p)$ is monotone around the solution, a high-precision solution can be obtained by limited number of iterations.

The increased angular momentum ΔL must also be reduced to zero. In order to do this, the method proposed by Kajita et al[4], which is to minimize the following function is used:

$$(x_{c'} - x_{c'}^O)^2 + (v_{c'} - v_{c'}^O)^2 \tag{7}$$

where $x_{c'}$ and $v_{c'}$ are the position and velocity of the COG at Point C' and $x_{c'}^0$ and $v_{c'}^0$ 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 minimize Equation 7. The motion during the double support phase is determined by solving for p using Equation 6.

One problem remains here; although the angular momentum can be reduced to zero by adjusting the AMPM parameters, the posture of the body will remain different from the original gait motion, unless angular momentum that bring the body to the original posture is generated. In order to solve this problem, we introduce a new criteria called *distortion of inertia*, which can be used to estimate the amount of additional angular momentum that must be added to the body to bring the body back to the original posture calculated by the feedforward controller. The distortion of inertia can be defined as follows:

$$\Delta I = \sum_i (c_i - c_g) \times (c_i - c_i^o) + R_i I_i R_i^T (\theta_i^o - \theta_i) \tag{8}$$

where c_i is the position of COG, c_i^o is the COG 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, as well, and c_g is the COG of the whole body. By dividing the distortion of inertia by the interval for the transition, it is possible to calculate the angular momentum needed to transfer to the goal posture. In order to recover the original motion inertia during 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 which can be calculated by dividing the distance between B and C by the velocity of the COG at Point B:

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

where $x_B, \dot{x_B}$, and x_C are the position and velocity of the COG at point B, and the position of Point C, as well.

Instead of solving for p using Equation 6, the following equation can be used to calculate the motion to recover the original posture:

$$\omega_{B,C} = \Delta M + \beta \frac{\Delta I}{\widetilde{T_{B,C}}} \tag{9}$$

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

Because we must decide all the parameters for the double support phase before the swing foot lands onto the ground, the distortion of the body at Point B must be estimated immediately after the external perturbation is applied to the body. Because the distortion of inertia is based on the posture of the body, it is necessary to estimate the posture of the body when the foot lands on to the land by the following equation:

$$\boldsymbol{q}'_B = T_{A,B}(\dot{\boldsymbol{q}}^o_A - \dot{\boldsymbol{q}}_A) + \boldsymbol{q}^o_B \tag{10}$$

where $\boldsymbol{q}'_B$ is the vector of the estimated generalized coordinates at Point B, $\boldsymbol{q}^o_B$ is the generalized coordinates at Point B in the original motion, $\dot{\boldsymbol{q}}^o_A$ and $\dot{\boldsymbol{q}}_A$ are the velocities of the generalized coordinates at Point A in the original motion and the current motion, as well, and $T_{A,B}$ is the duration before the swing foot lands onto the ground. Using this estimated generalized coordinate values, the distortion of the inertia will be estimated as follows:

$$\Delta I' = \sum_i (c'_i - c'_g) \times (c'_i - c^o_i) + R'_i I_i R'^T_i (\theta^o_i - \theta'_i) \tag{11}$$

where c^o_i and θ^o_i are the position of the COG and the orientation of segment i in the original motion, and c'_i, θ'_i and R'_i represent the estimated position of the COG, the estimated orientation, and the estimated 3×3 rotational matrix of segment i at Point B, as well, and c'_g represents the estimated position of the COG of the whole body.

The values of these parameters are all calculated by using $\boldsymbol{q}'_B$. Therefore, actually, the following equation will be used to solve for p:

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

For each of the following walking step, 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 9. For the distortion of inertia, the value at the end of the previous double support phase is used. As a result, the motion gradually returns back to the original motion after a few steps.

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

The motion of the COG in the frontal plane can be explained by AMPM as shown in Figure 3. During double support phase, the ZMP will move proportionally to the COG, and during single support phase, the ZMP will stay at the same position under the supporting foot. If we assume no angular momentum is generated, the vector connecting the COG 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 force vector is again always parallel to the vector connecting the COG and the ZMP in the original feedforward motion. External perturbation is applied to the body at Point A, during single support phase, as shown in Figure 3, and as a result, angular momentum of amount ΔM^f is induced around the frontal axis. In order to reduce this angular momentum to zero, the motion during the

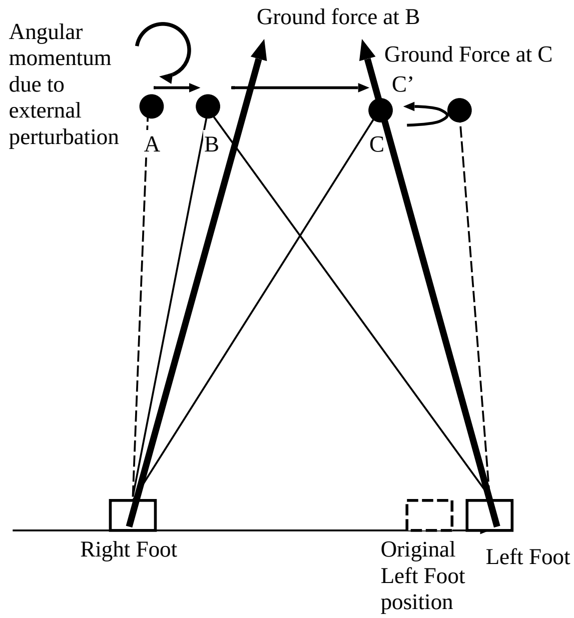

Figure 3: Counteracting the angular momentum induced by external perturbation in the frontal plane. External perturbation is applied during single support phase at Point A. The position of the foot landing on the ground will be changed, and the ground force vector at Point C will be changed, as well. The ground force vector during the rest of the trajectories will be calculated in a way that the acceleration is continuous. The motion of the double support phase will be calculated in a way that when the right foot lands onto the ground after the single support by the left foot (Point C'), the position and velocity of the COG will be close to those of the original feedforward motion, and the angular momentum is reduced to zero.

following double support phase and the single support phase will be modified. Again, the strategies (1) the position 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 counter act the angular momentum induced by the external perturbation, will be used, just as same as in the motion in the sagittal plane.

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

$$\ddot{y} = p_y y + q_y \tag{13}$$

where p_y, q_y are AMPM parameters. As 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

$$y_C = \frac{\sqrt{p_y}(y_B + \frac{d}{c} - \dot{y}_B)}{2} e^{-\sqrt{p_y}T_{B,C}} + \frac{\sqrt{p_y}(y_B + \frac{q_y}{p_y} + \dot{y}_B)}{2} e^{\sqrt{p_y}T_{B,C}} - \frac{q_y}{p_y}$$

$$\dot{y_C} = -\frac{p_y(y_B + \frac{p_y}{q_y} - \dot{y_B})}{2} e^{-\sqrt{p_y}T_{B,C}} + \frac{p_y(y_0 + \frac{d}{c} + \dot{y_B})}{2} e^{\sqrt{p_y}T_{B,C}}.$$

where $y_B, y_C, \dot{y_B}, \dot{y_C}$ are the positions and velocities of COG at Point B and Point C, as well. The calculation done here is quite similar to those done for the motion in the sagittal plane. To calculate p_y and q_y, the following two constraints are taken into account:

$$\omega_d = -\Delta M^f + \Delta I^{f\prime} \quad (14)$$

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

where $\Delta I^{f\prime}$ is the estimated distortion of inertia at Point B, and α is a constant value smaller than 1 to stabilize the convergence of the method.

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

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

where $y_{c'}$ and $\dot{y}_{c'}$ are the position and velocity of the COG 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 minimize Equation 16. The motion during the double support phase is determined by calculating the AMPM parameters p_y and q_y by using Equation 14 and 15 as constraints.

2.3 Calculating the joint angles using inverse kinematics

As we have already defined the trajectories of the COG and the angular momentum, the next step is to calculate kinematic parameters that satisfy these trajectories. Inverse kinematics is used for this purpose. A human body model with 40 degrees of freedom, as shown in Figure 4, was used. At first, positions and rotational trajectories of the feet, which are defined here as (p_l, θ_l) and (p_r, θ_r), are calculated using the foot step data specified in advance. Four key-frames of the support foot are specified as shown in Figure 5. The data includes the posture of the foot at initial contact, initial full contact, heel rise, and toe off. The x- component of the velocity of the foot of the swing leg when it is lifted from the ground is calculated by

$$v^0_{\text{swing}} = \frac{l_s}{T_{\text{swing}}}.$$

The final velocity when it lands on the ground is set to zero. The trajectory of the swung foot is calculated by interpolating the key-frames with a Bezier curve.

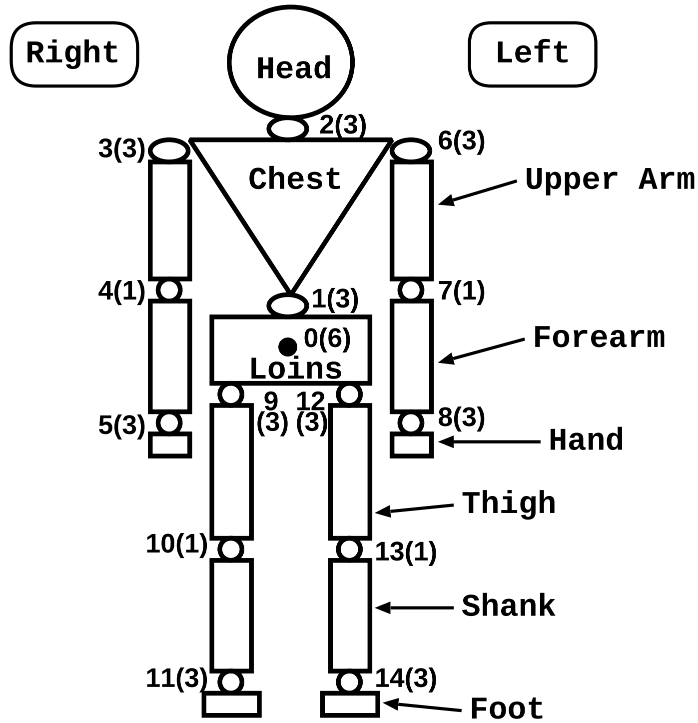

Figure 4: The human body model used in this study

Trajectories of generalized coordinates of the human body model are defined here as $\boldsymbol{q}(t) = (q_1(t), q_2(t), ..., q_{\rm dof}(t))^T$ where dof is the number of degrees of freedom of the human body model. 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 COG and velocity of the generalized coordinates can be written as follows:

$$\dot{\boldsymbol{x}}_g = J_{\rm cog}\,\dot{\boldsymbol{q}},$$

where $J_{\rm cog}$ is the Jacobian matrix that consists of the partial differentials of the

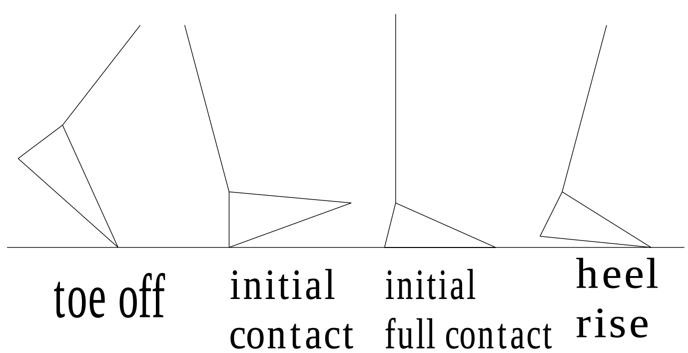

Figure 5: The key-frames of the foot rotation

COG by the generalized coordinates:

$$J_{\text{cog}} = \frac{\partial \boldsymbol{x}_g}{\partial \boldsymbol{q}}.$$

Then, the acceleration of the COG can be obtained as follows:

$$\ddot{\boldsymbol{x}}_g = J_{\text{cog}}\,\ddot{\boldsymbol{q}} + \dot{J}_{\text{cog}}\,\dot{\boldsymbol{q}}. \tag{17}$$

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

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

Then, the derivative of the angular momentum can be calculated as follows:

$$\dot{\boldsymbol{r}} = R\ddot{\boldsymbol{q}} + \dot{R}\dot{\boldsymbol{q}}. \tag{18}$$

Acceleration of the feet can be expressed as functions of $\ddot{\boldsymbol{q}}$ as well:

$$\begin{pmatrix} \ddot{\boldsymbol{p}}_l \\ \ddot{\boldsymbol{p}}_r \\ \ddot{\boldsymbol{\theta}}_l \\ \ddot{\boldsymbol{\theta}}_r \end{pmatrix} = J_f\ddot{\boldsymbol{q}} + \dot{J}_f\dot{\boldsymbol{q}} \tag{19}$$

Combining Equation 17, 18, and 19, linear constraints that must be satisfied can be written in the following form:

$$\boldsymbol{\lambda} = J_{\text{all}}\,\ddot{\boldsymbol{q}} + \dot{J}_{\text{all}}\,\dot{\boldsymbol{q}}. \tag{20}$$

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 $J_{\text{all}} = (J_{\text{cog}}, R, J_f)^T$. Calculating $\ddot{\boldsymbol{q}}$ that satisfies Equation 20 can be considered an inverse kinematics problem.

Since the goal is to calculate a stable gait motion, $\ddot{\boldsymbol{q}}$ that minimize the following quadratic form is calculated here:

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

where $\ddot{\hat{\boldsymbol{q}}}$ is the subset of $\ddot{\boldsymbol{q}}$ which determines an upright posture of the body. Those parameters include rotation of the loins and joint angles of the chest. $\hat{\boldsymbol{q}}_0$ is the target posture to keep the body upright, which is a zero vector here, and k, d are the elastic and the viscosity constants respectively.

$\ddot{\boldsymbol{q}}$ that minimize Equation 21 and satisfy Equation 20 were calculated through quadratic programming. 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.

3 Experiments

The motion of the human body was first generated by planning the motion of the COG using AMPM without any angular momentum around the COG. After the trajectories of the COG and the feet were determined, the trajectories of the joint angles were calculated using inverse kinematics. This motion is shown in Figure 6.

Then, while the humanoid is executing this feedforward motion, external perturbation were applied to the body during the single support phase. Two experiments were done and in each of them different level of impact were applied to the body. In the first experiment, a weaker impact impact that induced additional linear momentum of 0.1 $kg \cdot m/s$ and angular momentum of 12.0 $kg \cdot m^2/s$ around the COG. In the second experiment, stronger perturbation was applied, which induced additional linear momentum of 0.2 $kg \cdot m/s$ and angular momentum of 24.0 $kg \cdot m^2/s$

First, gait motions that only counteract the external perturbation and do not take into account the distortion of inertia were calculated. The results are shown in Figure 7 (weak perturbation) and 8 (strong perturbation), as well. Although the humanoid can stop the rotation of the chest, the chest remains bent for the following motion.

Next, the feedback controller that takes into account the distortion of inertia was used. Again, two experiments were done. In each of them different level of perturbation was applied and the same additional pair of linear and angular momentum (linear momentum of 0.1 $kg \cdot m/s$ and angular momentum of 12.0 $kg \cdot m^2/s$ by the weaker impact, and linear momentum of 0.2 $kg \cdot m/s$ and angular momentum of 24.0 $kg \cdot m^2/s$ by the stronger impact) were induced. After the perturbation, the thorax rotates to the front due to the increased angular momentum. This angular momentum is counteracted during the following double support phase, and the original gait motion is gradually recovered after a few steps. The trajectories of the two motions are shown in Figure 9 and 10, as well. In both of the motions, after stopping the rotation of the chest, it is brought back to the original upright posture.

The trajectories of the angular momentum around the lateral axis when the inertia distortion is taken into account (dashed line) and when it is not taken into account (solid line) are plotted in Figure 11. Without considering inertia distortion, the angular momentum just decreases to zero. On the other hand, when this information is used for feedback control, after the value decreases to zero, negative angular momentum that is needed to move the body back to the upright posture is generated, and gradually converges to zero after a few steps.

Figure 6: The original gait motion of the humanoid gait in the sagittal plane generated using AMPM.

4 Discussion

As the gait motion is much more unstable during the single support phase than during the double support phase, we assume here the external perturbation happened during the single support phase.

As the stance distance is much longer along the anterior axis than along the lateral axis, the method in this study is more effective for counteracting angular momentum around the lateral axis than around the frontal axis. Strong interference along the lateral axis will greatly affect the velocity of the COG and then the humanoid will have to step out the next step lateral to the supporting foot. In such case, however, the swing foot can easily collide with the supporting leg unless precise path planning is done for the landing motion. This would be the next subject to be solved.

The inertia criteria shows good performance to bring the current posture to the target posture. When calculating the motion using inverse kinematics by using the angular momentum and linear momentum as constraints as constraints, the obtained motion gradually deviates from the target motion even though the objective function of inverse kinematics include terms based on the difference of the target posture and the current posture. In such case, it is necessary to add additional angular momentum to the body in order to restore the original posture. By adding a term based on inertia criteria to the target angular momentum constraint, it is possible to stabilize the posture to the target posture.

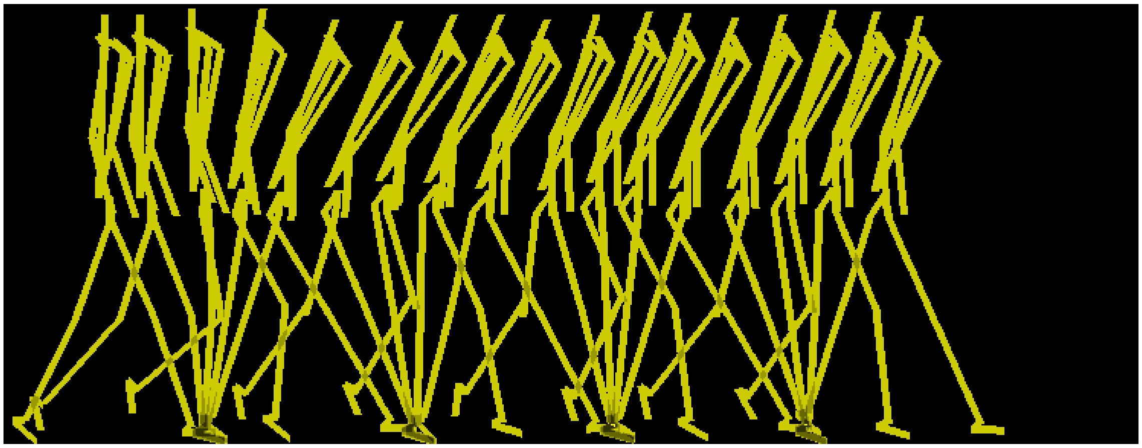

Figure 7: The trajectory of the humanoid walking in the sagittal plane. Assuming external perturbation has induced additional linear and angular momentum (0.1 $kg \cdot m/s$ and 12.0 $kg \cdot m^2/s$) during the single support phase, the increased angular momentum is counteracted during the following double support and single support phases.

5 Summary and Future Work

In this paper, we proposed a new method for biped humanoids to counteract a large amount of angular momentum induced by strong external perturbations applied to the body during gait motion. Such angular momentum can easily cause the humanoid to fall down onto the ground. We use AMPM, which is an enhanced version of 3DLIPM, to calculate the counteracting motion in real-time.

Although we assumed large amount of force as the external perturbation, the stepping patterns and the position of the foot landing to the ground were kept the same as the original feedforward motion. It is, however, not possible to counteract very strong perturbation especially in the lateral direction if the stepping pattern and the landing positions are also reorganized. Calculating new patterns of the appropriate stepping parameters will be the next goal to be achieved.

References

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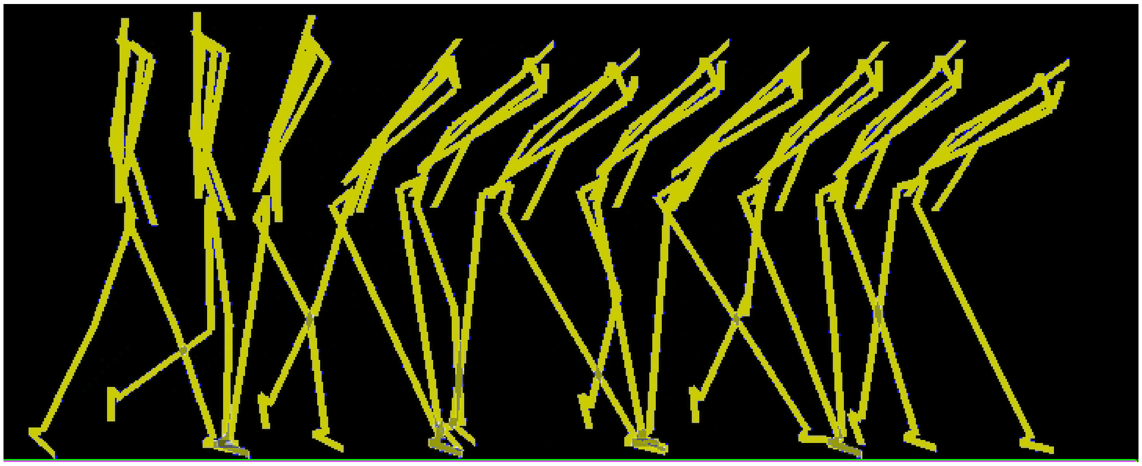

Figure 8: The trajectory of the humanoid walking in the sagittal plane. Assuming external perturbation has induced additional linear and angular momentum (0.2 $kg \cdot m/s$ and 24.0 $kg \cdot m^2/s$) during the single support phase, the increased angular momentum is counteracted during the following double support and single support phases.

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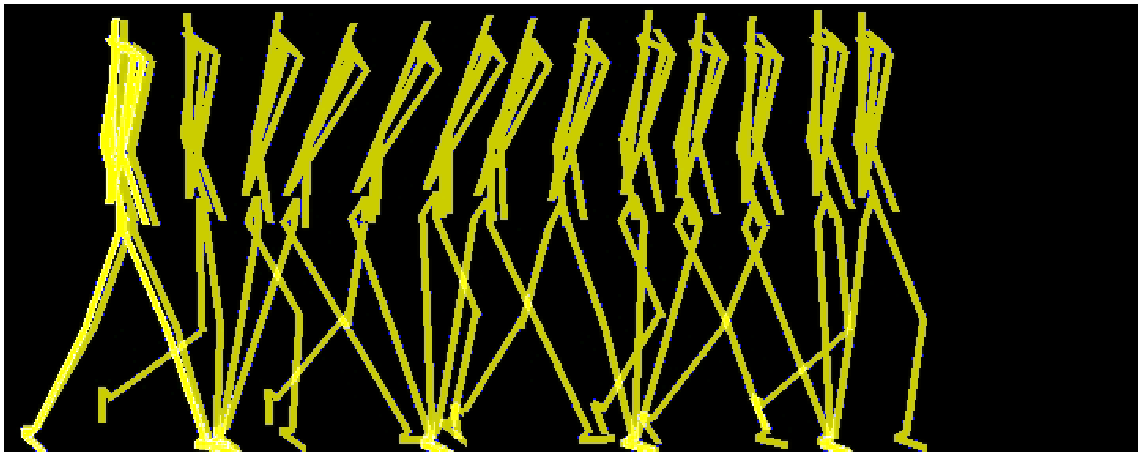

Figure 9: The motion of the humanoid gait in the sagittal plane. After 0.1 seconds in the initial single support phase, additional linear and angular momentum around the center of gravity is added to the body (0.1 $kg \cdot m/s$ and 12.0 $kg \cdot m^2/s$). The feedforward motion is reorganized so that the increased angular momentum can be counteracted during the following double support and single support phase.

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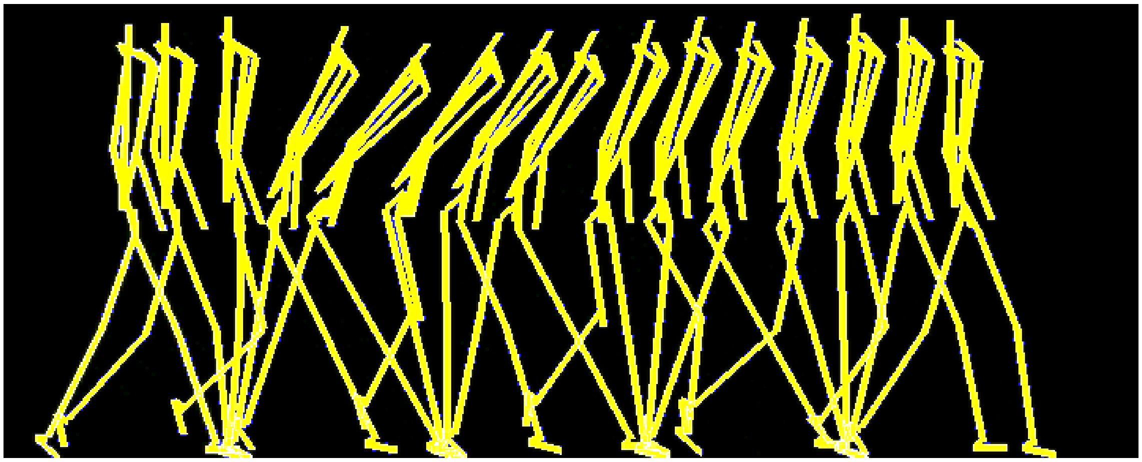

Figure 10: The motion of the humanoid gait in the sagittal plane. After 0.1 seconds in the initial single support phase, additional linear and angular momentum around the center of gravity is added to the body ($0.2\ kg \cdot m/s$ and $24.0\ kg \cdot m^2/s$). The feedforward motion is reorganized so that the increased angular momentum can be counteracted during the following double support and single support phase.

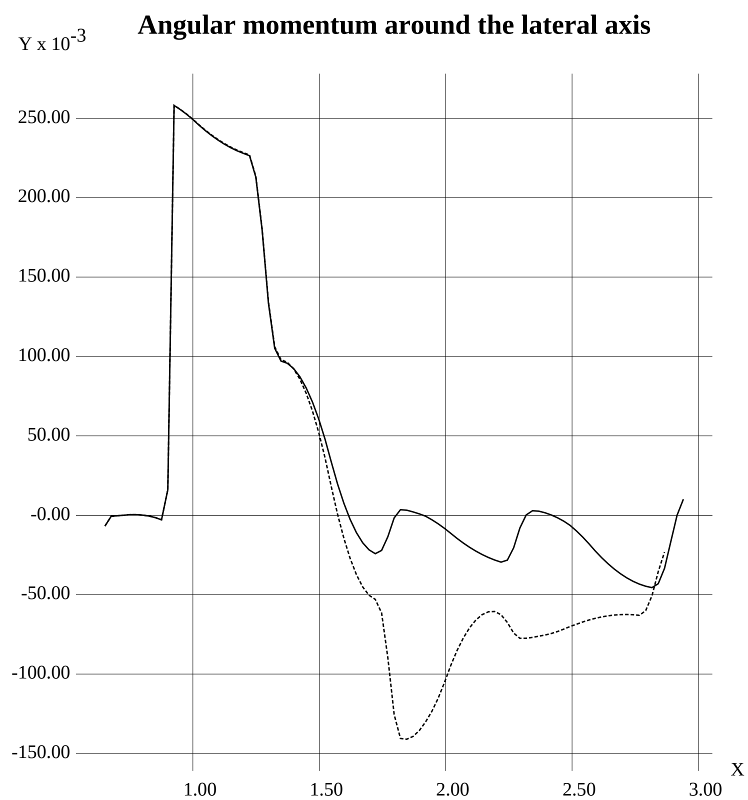

Figure 11: The trajectory of the angular momentum around the lateral axis when the AMPM is used only to counteract the angular momentum generated by the external perturbation (solid line), and when further angular momentum is generated for feedback motion to turn the motion back to the original gait