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Whole-body Cooperative Balancing of Humanoid Robot using COG Jacobian

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Abstract

Since humanoid robots have a number of degrees-of-freedom in general, a pattern-based approach of the motion control reduces its difficulty. It is necessary, however, to absorb and compensate disturbances in order to maintain the stability of robots in the real world. We developed a balancing method for humanoid robots with a little modification of pre-designed motion trajectories. The method proposed has an advantage that it is allowed to choose any combination of joints as modified properties, so that it has enough flexibility, being applicable for various types of robots and motions. It consists of two phases; in the first phase, the referential COG displacement is decided in accordance with both the short-term and the long-term absorption of disturbances. And in the second phase, the COG is manipulated with the whole-body cooperation, using the COG Jacobian. We verified the validity of the method with some simulations.

1 Introduction

Humanoid robots usually have so large number of degrees-of-freedom that it is hard to control them. Besides the fact, the higher-level operation robots are required to carry out, the severer constraints on both kinematics and dynamics are imposed on their motions. From this viewpoint, the pattern-based motion control has an advantage; operators may prepare proper trajectories of each joint to accomplish the task, considering the constraints in advance – avoiding collision with obstacles and keeping the physical consistency of the motion, for example – and simply get robots to replay them. The ways to design the trajectories have been proposed in a lot of previous works [1, 2, 3, 4].

In the real world, however, there are many kinds of disturbances such as modelization errors, unpredictable changes of the environment, sudden impacts and so forth. They often causes the unbalancedness of robots or even falling-down of them. Thus, an effective real-time stabilization method is required on the operations of real robots.

It is thought that, if the pre-designed trajectory is adequate in terms of both kinematics and dynamics, balance of the robot can be maintained with a little modification of the trajectory. Several methods on the basis of such idea have been proposed. Kajita et al. proposed a balancing method which directly controls the angular momentum around the ankle joint of the supporting leg, using torque control [5]. Since it uses only the ankle joint, loads concentrate to it. Furthermore, motion types that the method are applicable for are dissapointingly restricted to single-leg-supported ones. Huang et al.[6] and Park et al.[7] proposed real-time modification methods of pre-designed trajectories. They only treated walking on the sagittal plane. And the criterion of balancing they adopted is only about the ZMP(Zero Moment Point [8]), which is not enough to discuss the stability. Tamiya et al. developed Auto Balancer[9], which modifies the original input trajectories based on so many criteria of stability that it is hardly applicable for fast dynamic motions because of both the complexity of the algorithm and the criteria themselves. Nagasaka proposed Trunk Position Compliance Control [2]. Honda R&D Co.,Ltd. also suggested a compliance control strategy[10]. Though they are proved to be so powerful that they can realize dynamic motions of robots, the properties which the methods use to stabilize motions are limited to those of lower extremities. More flexible way that is allowed to use any combination of joints is expected.

In this paper, an efficient balancing method which manipulates the COG(Center of Gravity) with the whole-body cooperation using the COG Jacobian, considering both the short-term and the long-term absorption of disturbance is proposed. It has a enough flexibility to be applicable for robots with

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various kinematic structures and a lot of degrees-of-freedom, and for various types of motions, being allowed to choose any combination of joints as modified properties so far as it is sufficient to achieve balancing. And loads are dispersed to all joints with arbitrary weights. In spite of such the fact, it has less complexity so that it can be applied even for fast dynamic motions.

2 How To "Balance"

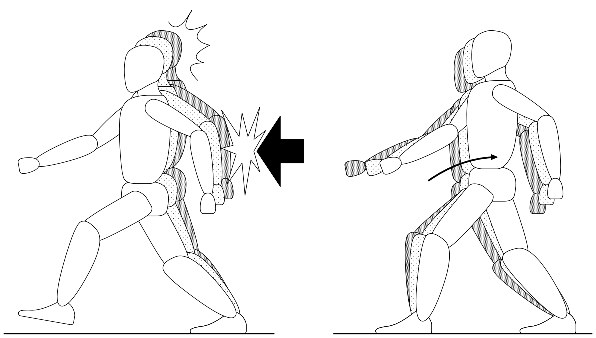


Figure 1: *Two basic schemes to balance*

The important factors to "balance" for legged motions are the following two.

- modification of the pre-designed trajectory of posture in order to conserve the contact condition (short-term absorption of disturbance)
- robust compensation of the error between the planned posture and the real(long-term absorption of disturbance)

The above two schemes are obviously in conflict with each other. In other words, "balancing" is thought to mean recovering the consistency of the condition between kinematics and dynamics with the mutual effect of the conflicting schemes (Fig.1 figures the concept). The former item corresponds to the conservation of dynamics condition through the modification of kinematic condition, while the latter corresponds to the recovery of kinematic condition through the modification of dynamics.

Human-beings realize such the conflicting schemes with the whole-body cooperation, manipulating the COG skillfully. Thus, it is expected to be effective for humanoid robots – anthropomorphic mechanisms – to implement the similar function, which leads to much more reliable and stable operations of them.

Suppose that a motion of humanoid robot is described with a set of joint angle vector $\boldsymbol{\theta}$, the COG $\boldsymbol{x}_G = [x_G \;\; y_G \;\; z_G]^T$, the ZMP $\boldsymbol{x}_Z = [x_Z \;\; y_Z \;\; z_Z]^T$, and the vertical component of ground reaction force f_z (z-axis coincides with the direction against gravity), and that the command set of the above parameters ${}^{cmd}\boldsymbol{\theta}$, ${}^{cmd}\boldsymbol{x}_G$, ${}^{cmd}\boldsymbol{x}_Z$, ${}^{cmd}f_z$ are given without any inconsistency between kinematics and dynamics, that is to say, when the real robot replays ${}^{cmd}\boldsymbol{\theta}$ strictly in the environment without any disturbances, the real $\boldsymbol{x}_G$, $\boldsymbol{x}_Z$ and f_z coincide with ${}^{cmd}\boldsymbol{x}_G$, ${}^{cmd}\boldsymbol{x}_Z$ and ${}^{cmd}f_z$ respectively. The method proposed calculates as close referential value of $\boldsymbol{\theta}$, ${}^{ref}\boldsymbol{\theta}$ which achieves the two conflicting schemes at the head of this section to the given ${}^{cmd}\boldsymbol{\theta}$ as possible. The outline of it is figured with Fig.2.

We considered that the problem of how to implement the function can be broken into the following two subproblems.

i) How to decide the referential COG displacement in order to balance

ii) How to manipulate the COG with the whole-body cooperation

The solutions we developed for each are shown in the following sections.

3 Decision of Referential COG Displacement

In this section, how to decide the referential COG displacement which recovers the consistency between the kinematics and dynamics conditions of the motion is shown.

3.1 Short-term Absorption of Disturbance

Unpredicted forces can let the sole of the supporting leg detach off the ground and let the robot upset. Trial to keep a stable contact condition between the sole and the ground, therefore, plays an important role for the avoidance of short-term crisis, namely, the short-term absorption of disturbance. When the actual point of action of the total external force, $\boldsymbol{x}_Z$ equivalently, and the vertical component of ground reaction force f_z coincide with ${}^{cmd}\boldsymbol{x}_Z$ which has an enough margin in *the supporting region*[11] and ${}^{cmd}f_z$ respectively, the contact between the sole and the ground is conserved stably.

Assuming a mass-concentrated model, the equation of motion is approximately expressed as:

$$(z_G - z_Z)m\ddot{x}_G - (x_G - x_Z)f_z = 0 \tag{1}$$

$$(z_G - z_Z)m\ddot{y}_G - (y_G - y_Z)f_z = 0 \tag{2}$$

$$m(\ddot{z}_G + g) = f_z \tag{3}$$

where m is the total mass of the robot, and g is the acceleration of gravity. Although the inertia of

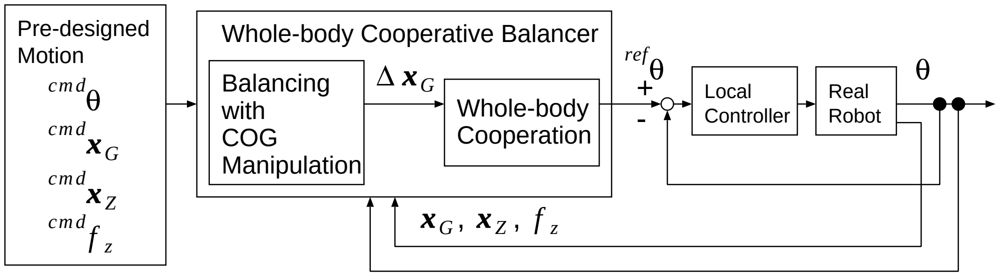


Figure 2: *Block diagram of the proposed balancing method with a real-time motion modification*

each link are ignored in these equations so that they are less accurate, the amount of computation is reduced enough to be suitable for real-time control. And we've verified on the simulation that the problem of accuracy is not critical for the operation.

Thus, giving the acceleration calculated in the following equations to each component of the COG, $\boldsymbol{x}_Z$ and f_z coincide with ${}^{cmd}\boldsymbol{x}_Z$ and ${}^{cmd}f_z$ respectively.

$$\ddot{x}_G = \zeta(x_G - {}^{cmd}x_Z) \tag{4}$$
$$\ddot{y}_G = \zeta(y_G - {}^{cmd}y_Z) \tag{5}$$
$$\ddot{z}_G = \frac{{}^{cmd}f_z}{m} - g \tag{6}$$

where ζ is defined by

$$\zeta \equiv \frac{{}^{cmd}f_z}{m(z_G - {}^{cmd}z_Z)} \tag{7}$$

Quantizing these equations with a small time step Δt, we get

$$\Delta x_{G,i+1} = \Delta x_{G,i} + \zeta_i(x_{G,i} - {}^{cmd}x_{Z,i})\Delta t^2 \tag{8}$$
$$\Delta y_{G,i+1} = \Delta y_{G,i} + \zeta_i(y_{G,i} - {}^{cmd}y_{Z,i})\Delta t^2 \tag{9}$$
$$\Delta z_{G,i+1} = \Delta z_{G,i} + \left(\frac{{}^{cmd}f_{z,i}}{m} - g\right)\Delta t^2 \tag{10}$$

where $*_i$ is a value of $*$ at the time i, and $\Delta *_{i+1}$ is defined by

$$\Delta *_{i+1} \equiv *_{i+1} - *_i \tag{11}$$

Now we've derived the conservation method of contact condition with a modification of motion, namely, a modification of kinematic condition for the recovery of dynamics condition.

3.2 Long-term Absorption of Disturbance

The operation shown in the previous subsection 3.1 can be regarded as a deformation of the preplanned motion in order to avoid the instantaneous crisis caused by disturbance. If the objective of the planned task is to let the robot perform according to the pre-designed trajectory, recovery of the COG to the desired position, which can be regarded on the contrary as the long-term absorption of disturbance, is also required. In order to realize it, the equations (8)(9)(10) are rewritten as follows, adding some terms for a compensation of the error between ${}^{cmd}\boldsymbol{x}_G$ and $\boldsymbol{x}_G$.

$$\begin{aligned}\Delta x_{G,i+1} &= \Delta x_{G,i} + \zeta_i(x_{G,i} - {}^{cmd}x_{Z,i})\Delta t^2 \\ &\quad + K_x \Delta^{cmd}x_{G,i} + D_x \Delta^{2cmd}x_{G,i}\end{aligned} \tag{12}$$
$$\begin{aligned}\Delta y_{G,i+1} &= \Delta y_{G,i} + \zeta_i(y_{G,i} - {}^{cmd}y_{Z,i})\Delta t^2 \\ &\quad + K_y \Delta^{cmd}y_{G,i} + D_y \Delta^{2cmd}y_{G,i}\end{aligned} \tag{13}$$
$$\begin{aligned}\Delta z_{G,i+1} &= \Delta z_{G,i} + \left(\frac{{}^{cmd}f_{z,i}}{m} - g\right)\Delta t^2 \\ &\quad + K_z \Delta^{cmd}z_{G,i} + D_z \Delta^{2cmd}z_{G,i}\end{aligned} \tag{14}$$

where $\Delta^{cmd}*_{G,i}$ and $\Delta^{2cmd}*_{G,i}$ are defined by

$$\Delta^{cmd}*_{G,i} \equiv {}^{cmd}*_{G,i} - *_{G,i} \tag{15}$$
$$\Delta^{2cmd}*_{G,i} \equiv \Delta^{cmd}*_{G,i} - \Delta^{cmd}*_{G,i-1} \tag{16}$$

respectively, and K_*, D_* are the proportional gain and the differential gain respectively for the compensation of each component of the error ($*$ is substituted for x, y or z).

As a consequence, the referential COG displacement is decided by the equations (12)(13)(14).

These equations can also be represented as the followings.

$$\begin{aligned}&\Delta x_{G,i+1} = \Delta x_{G,i} + \zeta_i(x_{G,i} - {}^{ref}x_{Z,i})\Delta t^2, \\ &{}^{ref}x_{Z,i} = {}^{cmd}x_{Z,i} - \frac{K_x \Delta^{cmd}x_{G,i} + D_x \Delta^{2cmd}x_{G,i}}{\zeta_i \Delta t^2}\end{aligned} \tag{17}$$
$$\begin{aligned}&\Delta y_{G,i+1} = \Delta y_{G,i} + \zeta_i(y_{G,i} - {}^{ref}y_{Z,i})\Delta t^2, \\ &{}^{ref}y_{Z,i} = {}^{cmd}y_{Z,i} - \frac{K_y \Delta^{cmd}y_{G,i} + D_y \Delta^{2cmd}y_{G,i}}{\zeta_i \Delta t^2}\end{aligned} \tag{18}$$
$$\begin{aligned}&\Delta z_{G,i+1} = \Delta z_{G,i} + \left(\frac{{}^{ref}f_{z,i}}{m} - g\right)\Delta t^2, \\ &{}^{ref}f_z = {}^{cmd}f_z + \frac{m(K_z \Delta^{cmd}z_{G,i} + D_z \Delta^{2cmd}z_{G,i})}{\Delta t^2}\end{aligned} \tag{19}$$

where ${}^{ref}x_{Z,i}$ and ${}^{ref}y_{Z,i}$ are the horizontal components of the actual referential ZMP, and ${}^{ref}f_z$ is the vertical component of the actual referential ground reaction force. It is possible, therefore, to regard the above procedure as an indirect ZMP manipulation and the ground reaction force for stabilization, namely, a modification of dynamics condition for the recovery of kinematic condition. The requirement of such manipulation of external force underlies the fact that humanoid robots are under-actuated system in nature. Since the ZMP has to be located in the supporting region and the ground reaction force has to be positive, each gain, K_* and D_*, should be chosen adaptively as adequate values which can conserve the stable contact condition (Fig.3). (In this paper, they are fixed as small values for simplicity.)

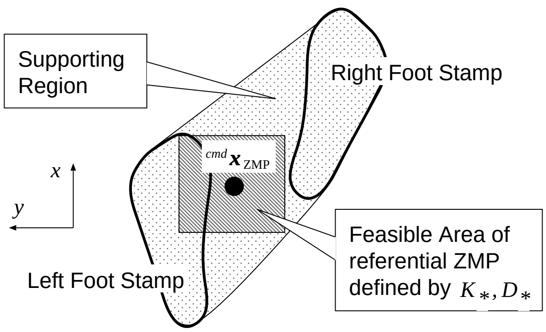


Figure 3: *Feasible area of the referential ZMP*

4 COG Manipulation with Whole-body Cooperation

In this section, how to manipulate the COG with the whole-body cooperation is described. First of all, we derive the COG Jacobian, which has been already introduced in [11], in the following subsection 4.1. And then, using it, we give a solution to how to calculate the quantized displacement of $\boldsymbol{\theta}$, $\Delta\boldsymbol{\theta}_{i+1}$ which can give $\Delta\boldsymbol{x}_{G,i+1}$ to the COG in subsection 4.2.

4.1 COG Jacobian

The COG $\boldsymbol{x}_G$ is expressed as a function with an argument $\boldsymbol{\theta}$ like $\boldsymbol{x}_G(\boldsymbol{\theta})$ in general. Thus, there exists a Jacobian $\boldsymbol{J}_G$ which relates $\dot{\boldsymbol{\theta}}$ to $\dot{\boldsymbol{x}}_G$ as:

$$\dot{\boldsymbol{x}}_G = \boldsymbol{J}_G\dot{\boldsymbol{\theta}} \tag{20}$$

This is the COG Jacobian, defined by

$$\boldsymbol{J}_G \equiv \frac{\partial \boldsymbol{x}_G}{\partial \boldsymbol{\theta}} \tag{21}$$

Although $\boldsymbol{x}_G$ is a quite complex non-linear function with multiple arguments, $\boldsymbol{J}_G$ is able to be calculated rather fast and accurately with the following numerical approach.

Firstly, The relative COG velocity with respect to the total body coordinate system Σ_0. ${}^0\dot{\boldsymbol{x}}_G$ is expressed as:

$${}^0\dot{\boldsymbol{x}}_G = \frac{\sum_{k=0}^{n-1} m_k {}^0\dot{\boldsymbol{r}}_k}{\sum_{k=0}^{n-1} m_k} = \frac{\sum_{k=0}^{n-1} m_k {}^0\boldsymbol{J}_{Gk}\dot{\boldsymbol{\theta}}}{\sum_{k=0}^{n-1} m_k} \tag{22}$$

where n is a degree of freedom of the robot, m_k is the mass of link k, ${}^0\boldsymbol{r}_k$ is the position of the center of mass of link k with respect to Σ_0, and ${}^0\boldsymbol{J}_{Gk}$ is defined by

$${}^0\boldsymbol{J}_{Gk} \equiv \frac{\partial {}^0\boldsymbol{r}_k}{\partial \boldsymbol{\theta}} \tag{23}$$

And the equation(22) is simplified as:

$${}^0\dot{\boldsymbol{x}}_G = {}^0\boldsymbol{J}_G\dot{\boldsymbol{\theta}} \tag{24}$$

where ${}^0\boldsymbol{J}_G$ is defined by

$${}^0\boldsymbol{J}_G \equiv \frac{\sum_{k=0}^{n-1} m_k {}^0\boldsymbol{J}_{Gk}}{\sum_{k=0}^{n-1} m_k} \tag{25}$$

Secondly, suppose link F is fixed in the world coordinate system Σ_w(for example, when the right leg is the supporting leg, the right foot link is fixed), the COG velocity with respect to Σ_w, $\dot{\boldsymbol{x}}_G$, is calculated as:

$$\begin{aligned}\dot{\boldsymbol{x}}_G &= \dot{\boldsymbol{x}}_0 + \boldsymbol{\omega}_0 \times \boldsymbol{R}_0{}^0\boldsymbol{x}_G + \boldsymbol{R}_0{}^0\dot{\boldsymbol{x}}_G \\ &= \boldsymbol{R}_0\{{}^0\dot{\boldsymbol{x}}_G - {}^0\dot{\boldsymbol{p}}_F + ({}^0\boldsymbol{x}_G - {}^0\boldsymbol{p}_F) \times {}^0\boldsymbol{\omega}_F\} \\ &= \boldsymbol{R}_0\{{}^0\boldsymbol{J}_G - {}^0\boldsymbol{J}_F + [({}^0\boldsymbol{x}_G - {}^0\boldsymbol{p}_F)^\times]{}^0\boldsymbol{J}_{\omega F}\}\dot{\boldsymbol{\theta}}\end{aligned} \tag{26}$$

where $\boldsymbol{x}_0$ is the position of the base link in Σ_w, $\boldsymbol{\omega}_0$ is the rotation velocity of the base link with respect to Σ_w, $\boldsymbol{R}_0$ is the attitude matrix of the base link with respect to Σ_w, ${}^0\boldsymbol{p}_F$ is the position of the fixed link in Σ_0, ${}^0\boldsymbol{\omega}_F$ is the rotation velocity of the fixed link with respect to Σ_0, ${}^0\boldsymbol{J}_F$ is the Jacobian about linear velocity of the fixed link with respect to Σ_0, ${}^0\boldsymbol{J}_{\omega F}$ is the Jacobian about rotation velocity of the fixed link with respect to Σ_0, and $[\boldsymbol{v}^\times]$ means outer-product matrix of a vector $\boldsymbol{v}$ (3×1).

Thus, $\boldsymbol{J}_G$ is calculated as:

$$\boldsymbol{J}_G = \boldsymbol{R}_0\{{}^0\boldsymbol{J}_G - {}^0\boldsymbol{J}_F + [({}^0\boldsymbol{x}_G - {}^0\boldsymbol{p}_F)^\times]{}^0\boldsymbol{J}_{\omega F}\} \tag{27}$$

4.2 Decision of the Whole-body Motion

As a result of adding $\Delta\boldsymbol{\theta}_{i+1}$ to the current joint angle vector $\boldsymbol{\theta}_i$ until the next step, $\boldsymbol{\theta}_{i+1}$ should be as close value to ${}^{cmd}\boldsymbol{\theta}_{i+1}$ as possible. This problem can be interpreted to the following quadratic programming with equational constraints.

$$\begin{aligned}&\frac{1}{2}(\Delta^{cmd}\boldsymbol{\theta}_{i+1} - \Delta\boldsymbol{\theta}_{i+1})^T\boldsymbol{W}(\Delta^{cmd}\boldsymbol{\theta}_{i+1} - \Delta\boldsymbol{\theta}_{i+1}) \\ &\qquad\longrightarrow \min. \\ &\text{subject to} \quad \begin{cases}\boldsymbol{J}_{G,i}\Delta\boldsymbol{\theta}_{i+1} = \Delta\boldsymbol{x}_{G,i+1} \\ \boldsymbol{J}_{C,i}\Delta\boldsymbol{\theta}_{i+1} = \boldsymbol{c}_{i+1}\end{cases}\end{aligned} \tag{28}$$

where $\boldsymbol{W}$ is the weighting matrix, $\boldsymbol{J}_{G,i}$ is the COG Jacobian at i'th step, and $\Delta^{cmd}\boldsymbol{\theta}_{i+1}$ is defined by

$$\Delta^{cmd}\boldsymbol{\theta}_{i+1} \equiv {}^{cmd}\boldsymbol{\theta}_{i+1} - \boldsymbol{\theta}_i \qquad (29)$$

$\boldsymbol{J}_{C,i}\Delta\boldsymbol{\theta}_{i+1} = \boldsymbol{c}_{i+1}$ means the additional constraint needed for the task. Combining it with the constraint about the COG, it is simplified as:

$$\boldsymbol{J}_{U,i}\Delta\boldsymbol{\theta}_{i+1} = \boldsymbol{u}_{i+1} \qquad (30)$$

Now, (28) is equivalent to the following equation:

$$\begin{bmatrix} \boldsymbol{W} & \boldsymbol{J}_{U,i}^T \\ \boldsymbol{J}_{U,i} & \boldsymbol{O} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{\theta}_{i+1} \\ \boldsymbol{\lambda} \end{bmatrix} = \begin{bmatrix} \boldsymbol{W}\Delta^{cmd}\boldsymbol{\theta}_{i+1} \\ \boldsymbol{u}_{i+1} \end{bmatrix} \qquad (31)$$

where $\boldsymbol{\lambda}$ is the co-state vector of $\Delta\boldsymbol{\theta}_{i+1}$.

Solving (31), we can get

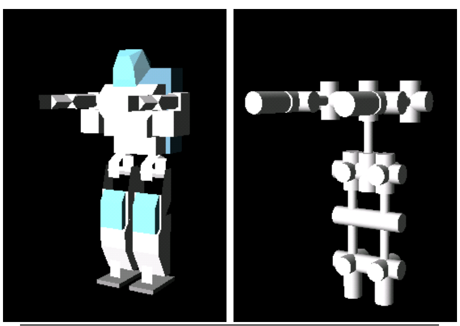
$$\begin{aligned} \Delta\boldsymbol{\theta}_{i+1} &= \Delta^{cmd}\boldsymbol{\theta}_{i+1} \\ &\quad + \boldsymbol{W}^{-1}\boldsymbol{J}_{U,i}^T(\boldsymbol{J}_{U,i}\boldsymbol{W}^{-1}\boldsymbol{J}_{U,i}^T)^{-1}\boldsymbol{v}_{i+1} \qquad (32) \\ \boldsymbol{v}_{i+1} &\equiv \boldsymbol{J}_{U,i}\Delta^{cmd}\boldsymbol{\theta}_{i+1} - \boldsymbol{u}_{i+1} \end{aligned}$$

And

$${}^{ref}\boldsymbol{\theta}_{i+1} = \boldsymbol{\theta}_i + \Delta\boldsymbol{\theta}_{i+1} \qquad (33)$$

Giving an adequate $\boldsymbol{W}$, an efficient whole-body cooperative motion is achieved. And then, robot motion can be stabilized.

5 Simulation



DOF:	20 (8 for arm,12 for leg)
height:	480 [mm]
weight:	6.5 [kg]

Figure 4: *Kinematic structure, size and mass of the robot*

We verified the method in some simulations, using a model of HOAP-1(Fujitsu Automation Ltd.)[12]. Kinematic structure, size and mass of the robot are shown in Fig.4.

Fig.5 is a snapshot of a simple motion, keeping the initial standing posture under some impulsive disturbances generated at random. And Fig.6 shows the loci of each component of the COG. Fig.7 is a snapshot of walking motion which is also under some impulsive disturbances. Fig.8 shows the loci of each component of the COG. In both cases, Δt was set for $1[msec]$.

These figures denote the method proposed works as expected in both cases, letting the whole-body of the robot cooperate, absorbing disturbances and recovering posture to the desired, namely, balancing.

6 Conclusion

In this paper, we showed that balancing of humanoid robot is achieved by the combination of both the short-term and the long-term absorption of disturbance, recovering the consistency between kinematics and dynamics. And, based on it, we proposed an effective balancing method for humanoid robots with a little modification of pre-designed motion trajectories. The effectiveness of it was verified with some simulations.

The method proposed has enough flexibility to be applied for robots with various kinematic structure and a lot of degrees-of-freedom and for various types of motions, dispersing loads to all joints with arbitrary weights. In addition, it has less amount of computation, applicable even for fast dynamic motions.

Acknowledgments

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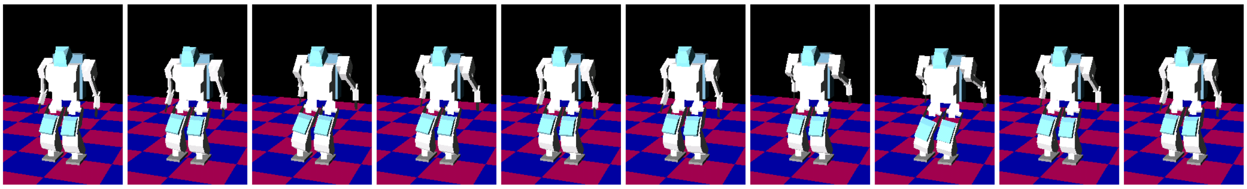

Figure 5: *Snapshots of a Simulation of Balance Control on Standing*

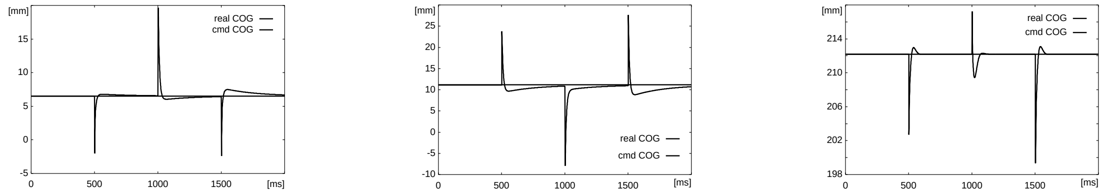

Figure 6: *Loci of the COG along x, y, z axes*

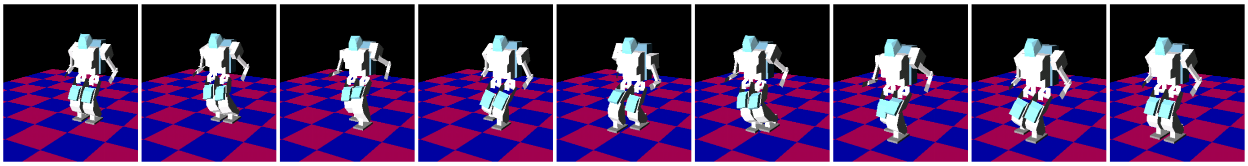

Figure 7: *Snapshots of a Simulation of Balance Control on Walking*

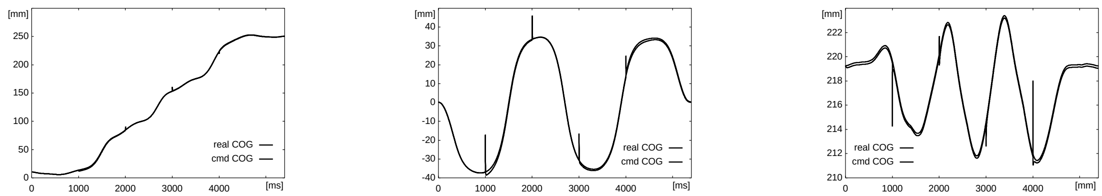

Figure 8: *Loci of the COG along x, y, z axes*

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