Proceedings of the 2009 IEEE
International Conference on Robotics and Biomimetics
December 19 -23, 2009, Guilin, China

Whole-Body Humanoid Balance Control with Dynamically Loading/Unloading Objects

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***Abstract*— When a humanoid lifts a heavy object, or carries an object in a bag or a carriage, it needs to change the reference CoM(center of mass) and ZMP(Zero Moment Position) in order not to fall down. However, it is not natural to design a reference CoM and ZMP to lift or to carry an object every time. In this paper, objects held by a hand are considered as an augmented virtual link connected at the end of the hand, and it is included in calculating the humanoid CoM. The mass augmentation is done in real time and thus objects can be loaded and unloaded dynamically without any change of reference CoM and ZMP. The balanced pose of the humanoid is obtained by using MECoM(Motion-Embedded CoM) Jacobian resolution method. The proposed method is verified by an experiment.**

I. INTRODUCTION

Mobility of a humanoid has been a main research issues up to now. However, in order for a humanoid to be useful to human's daily life, it needs to perform tasks with arms such as moving, carrying, and manipulating objects. For these object manipulating tasks, a humanoid needs to implement many manipulation methods and a balancing control is also needed, simultaneously. Especially, if a heavy object is manipulated, a whole body motion needs to be considered for stability.

Harada, *et al*[1], [2], [3], [4] uses GZMP(Generalized ZMP) to push or to lift up a heavy object. Arisumi, *et al*[5], [6] discussed a dynamic lifting which generate a whole body motion by using an inertia of objects actively to lift up a heavy object.

As shown in the previous research, the reference CoM and ZMP are trying to be changed to stabilize a humanoid in pushing or lifting a heavy object. However, if mass of the manipulated object is changed dynamically, for example, adding or removing an object to a cart or a shopping bag, it is complicated to generate a reference CoM and ZMP in real time.

For a human, as shown in Fig. 1, if a heavy object is added to a bag held by a hand, one inclines one's body to the opposite side of the object for body balancing. This whole body motion makes CoM and ZMP stay in the stable region automatically. If a human feels an object attached on the hand, one estimates its mass, and the reaction forces on the feet give a stability information, i.e., ZMP to human. By combining two estimated values, human can generate a motion for stable pose. In the figure, the line of body center(dotted line) is deviated from the ZMP when a human carrying a heavy object, but CoM including the object is replaced the original human CoM, *i.e.*, a human considers that a carrying object is a part of oneself to balance one's body.

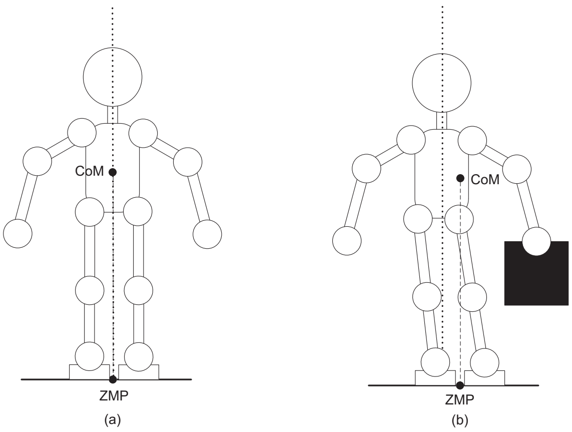

Fig. 1. CoM and ZMP relation (a) without and (b) with an object

In this paper, this automatic balancing is obtained for a humanoid with similar procedures of a human being by using a mass augmentation concept. An object attached on the wrist is considered as a virtual part of a humanoid, *i.e.*, the humanoid has a virtual link with variable mass on the hand. With this mass augmentation concept, humanoid balance with dynamically loaded and unloaded object can be easily stabilized without any change of the reference CoM and ZMP.

In order to accomplish this automatic balancing motion, the problem is divided into two stages: 1) to estimate mass of an object loaded on the hand for augmentation, and 2) to generate a whole body motion for stable pose. Mass and CoM of loaded object are estimated by using the 6-axis force/torque sensor attached on the wrist. The estimated mass and CoM are augmented in calculating the humanoid CoM as if it were a normal link of the humanoid. The augmented humanoid CoM is deviated from the reference CoM and the whole body motion can be generated to reduce the CoM deviation. The whole body motion is generated by using the resolution of MECoM(Motion Embedded CoM) Jacobian proposed by Y.J. Choi, *et al*[7], [8].

This paper is organized as follows: section II explains the resolution of MECoM Jacobian and the CoM-ZMP controller, briefly, and section III describes estimation of object

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978-1-4244-4775-6/09/$25.00

mass and augmentation it into the humanoid. Section IV shows the experimental result of the proposed method and section V concludes this paper.

II. MECoM JACOBIAN

Let us consider a n-DOF humanoid. There are two referential frames to describe a humanoid. The world coordinate frame is fixed on somewhere in the world and represents the global motion of a humanoid. The body center frame is fixed on a humanoid to describe the local motion. Almost all the properties of a humanoid are described in the body center frame. The leading superscript ${}^{o}(\cdot)$ implies that the elements are represented in the body center frame, and without it, a value is based on the world coordinate frame.

The CoM, $\mathbf{p}_G$, of a humanoid is a function of joint angle vector, $\mathbf{q}$, *i.e.*, $\mathbf{p}_G = \mathbf{f}(\mathbf{q})$. Thus, there exists a Jacobian $\mathbf{J}_G$ which can relate $\dot{\mathbf{q}}$ to $\dot{\mathbf{p}}_G$ as:

$$\dot{\mathbf{p}}_G = \mathbf{J}_G \dot{\mathbf{q}} \tag{1}$$

where the $(3 \times n)$ matrix $\mathbf{J}_G$ is defined by

$$\mathbf{J}_G \equiv \frac{\partial \mathbf{p}_G}{\partial \mathbf{q}} \tag{2}$$

We call $\mathbf{J}_G$ the CoM Jacobian hereafter. $\mathbf{p}_G$ is a quite complex function with multiple arguments.

Kagami, *et al*[9], proposed the numerical method to calculate it, which unfortunately needs a large amount of computation. Sugihara, *et al*[10], developed a fast and accurate calculation method and the result is summarized as follows.

The final form of the CoM velocity with respect to the world coordinates frame, $\dot{\mathbf{p}}_G$ is

$$\dot{\mathbf{p}}_G = \sum_{i=1}^{s} \mathbf{J}_{G,i} \dot{\mathbf{q}}_i + \mathbf{J}_{p1} \dot{\mathbf{q}}_1 \tag{3}$$

where s is the number of sections. The section used in the paper means the limb of a humanoid, *i.e.*, left arm, right arm, and etc. $\dot{\mathbf{q}}_i$ is the joint velocity of section i and especially, $\dot{\mathbf{q}}_1$ is the joint velocity of the base section. Note that the base section can be any section which is fixed on the ground, and here, the base section is assumed to have index number 1 without loss of generality. $\mathbf{J}_{G,i}$ is the CoM matrix of section i, and $\mathbf{J}_{p1}$ is the matrix relation between the base section and the humanoid CoM.

In Eq. (3), the first term is the summation of all the CoM velocity generated by each section with the CoM Jacobian of each section and the second term represents the relative linear velocity of CoM induced by the base section from the world coordinate system .

In order to embed a motion, Eq. (3) is modified according to the given motion type: a joint motion and a Cartesian motion. For simplicity, we assume that a motion is assigned to each section, for the resolution of the MECoM Jacobian.

A given motion changes the CoM relation shown in Eq. (3) as follows: if a joint motion, $\dot{\mathbf{q}}_{di}$ is given, the motion of the given section is fixed by the given joint motion and the resulting effect, $\dot{\mathbf{p}}_{G,i}$ to the whole-body CoM is determined. If a Cartesian motion, $\dot{\mathbf{x}}_{di}$ is given, CoM variation due to the given motion is expressed by the combination of the effect of the Cartesian motion, $\mathbf{f}_i(\dot{\mathbf{x}}_{di})$ and the joint motion expressed by the base section, $\mathbf{J}_{G,i1}\dot{\mathbf{q}}_1$, where $\mathbf{J}_{G,i1}$ is a matrix relating two sections.

After modifying the CoM Jacobin shown in Eq. (3), the final form of the MECoM Jacobian relation becomes

$$\dot{\mathbf{p}}_G - \sum \mathbf{J}_{G,i}\dot{\mathbf{q}}_{di} - \sum \mathbf{f}_i(\dot{\mathbf{x}}_{di}) = (\sum \mathbf{J}_{G,i1} + \mathbf{J}_{p1})\dot{\mathbf{q}}_1$$
$$\dot{\mathbf{p}}_{G,M} = \mathbf{J}_{G,M}\dot{\mathbf{q}}_1 \tag{4}$$

where $\dot{\mathbf{p}}_{G,M}$ and $\mathbf{J}_{G,M}$ are the modified CoM velocity and the CoM Jacobian, respectively.

For given reference CoM velocity, $\dot{\mathbf{p}}_G$ and desired motion for each section, a balanced joint motion of the base section, $\dot{\mathbf{q}}_1$, can be obtained by using Eq. (4). After obtaining $\dot{\mathbf{q}}_1$, desired joint motion of other sections, $\dot{\mathbf{q}}_i$, also can be obtained by using the relations shown in the above algorithm.

A pseudo code for modifying the original CoM Jacobian relation, Eq. (3), to obtain the MECoM Jacobian relation is given as follows.

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for all section i **do**
    get assigned motion
    if joint motion ($\dot{\mathbf{q}}_{di}$) **then**
        $\dot{\mathbf{p}}_{G,i} = \mathbf{J}_{G,i}\dot{\mathbf{q}}_{di}$
    else if Cartesian motion ($\dot{\mathbf{x}}_{di}$) **then**
        $\mathbf{J}_{G,i}\dot{\mathbf{q}}_{di} = \mathbf{f}_i(\dot{\mathbf{x}}_{di}) + \mathbf{J}_{G,i1}\dot{\mathbf{q}}_1$
    end if
end for
Solve Eq. (4) to get $\dot{\mathbf{q}}_1$
for all section i except the base section **do**
    if joint motion **then**
        known desired motion, $\dot{\mathbf{q}}_{di}$
    else if Cartesian motion **then**
        Solve $\mathbf{J}_{G,i}\dot{\mathbf{q}}_{di} = \mathbf{f}_i(\dot{\mathbf{x}}_{di}) + \mathbf{J}_{G,i1}\dot{\mathbf{q}}_1$
        to get $\dot{\mathbf{q}}_{di}$
    end if
end for

The reference CoM motion, $\dot{\mathbf{p}}_G$ is given before solving the MECoM Jacobian, which is controlled by the CoM-ZMP controller. The controller is obtained from the inverted pendulum model, and the form of the controller is

$$\dot{\mathbf{p}}_G = \dot{\mathbf{p}}_{Gd} + K_G \Delta \mathbf{p}_G - K_z \Delta \mathbf{p}_z \tag{5}$$

where K_G and K_z are gain for CoM and ZMP, respectively. $\Delta \mathbf{p}_G$ and $\Delta \mathbf{p}_z$ are error for CoM and ZMP, respectively. With this controller, CoM and ZMP are controlled simultaneously.

Overall control flow for the MECoM Jacobian is shown in Fig. 2. A detail explanation of modification of MECoM Jacobian and CoM-ZMP controller can be found in the paper[7], [8].

III. OBJECT MASS AUGMENTATION

In order to estimate mass and CoM of loaded object, a 6-axis F/T sensor is used on the wrist. From the measured

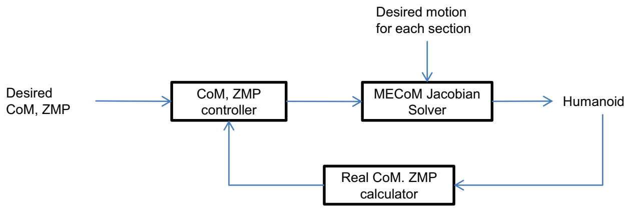

Fig. 2. Control Flow for MECoM Jacobian

force and torque, mass and CoM can be obtained easily by using the wrench relation.

If there is no external force, relation between object mass, m, and measured force, $\mathbf{f}$, is

$$m^2 = \frac{\mathbf{f}^T\mathbf{f}}{\mathbf{a}^T\mathbf{a}} \tag{6}$$

where $\mathbf{a}$ is the total acceleration of the object, *i.e.*, it includes the gravitational acceleration, $\mathbf{g}$, and an acceleration of motion, $\mathbf{a}_m$. If the loaded object has no motion, the acceleration is merely the gravitational acceleration, $\mathbf{a} = \mathbf{g}$.

The center of mass, $\mathbf{r}$, also can be obtained with the wrench relation as follows:

$$\mathbf{r} = \frac{\mathbf{f} \times \mathbf{n}}{\mathbf{f}^T\mathbf{f}} \tag{7}$$

where $\mathbf{n}$ is the measured torque.

With this simple relations shown in Eq. (6) and Eq. (7), a real-time estimation for a loaded object is possible without any prior information on the object. A detail explanation of object mass and CoM estimation is shown in [11].

Now we have mass information of a loaded object, and it is considered as a virtual link attached on the grasping hand. Mass, m_l, and CoM, $\mathbf{r}_l$, of the virtual link becomes

$$m_l = m_h + m \tag{8}$$

$$\mathbf{r}_l = \frac{m_h\mathbf{r}_h + m\mathbf{r}}{m_l} \tag{9}$$

where m_h and $\mathbf{r}_h$ are mass and CoM of the hand, respectively, which is predetermined in developing a humanoid robot. m and $\mathbf{r}$ are obtained from Eq. (6) and Eq. (7).

With this simple mass augmentation method, the real CoM of a humanoid can be changed automatically according to loaded and unloaded object. With this CoM augmentation, the desired CoM assigned for control needs not to be changed for a certain motion. For example, if a CoM-ZMP pattern is developed for walking along a line without carrying an object, we can use that pattern without any modification even if the robot carries a heavy object, since the mass effect is automatically augmented in the robot, and the real CoM-ZMP will follow the desired CoM-ZMP pattern. The next section will verify the mass augmentation method with an experiment.

IV. EXPERIMENT

The mass augmentation method is verified with a humanoid robot, **Mahru**, developed at KIST in 2004. In this paper, the experiment is an initial work to show the effect of the mass augmentation method. The humanoid, Mahru, is in standing still with a basket, and objects will be loaded and unloaded arbitrarily. The basket is held on the right arm, and for variation of objects, two kinds of objects are used: three small objects with 0.5kg and one object with 2kg. Figure 3 shows the humanoid with a basket and objects are loaded in sequence. As shown in the figure, the humanoid balances its body by moving itself automatically to the opposite side of the basket as loading objects.

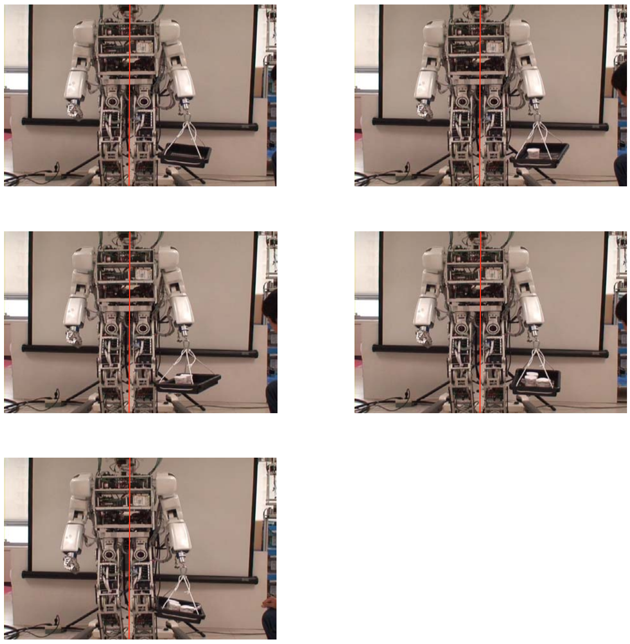

Fig. 3. Mahru with objects loaded in a basket

Teh resulting graphs for the CoM-ZMP and the pelvis movement when objects are loaded and unloaded shown in Fig. 3, are depicted in Fig. 4, Fig. 5, and Fig. 6.

Figure 4 shows the movement without CoM-ZMP control. In this case, by loading objects, the real CoM-ZMP is changed from the center of the body to the objects position(along the positive y axis). However, the pelvis position of the humanoid is not changed, *i.e.*, no reaction against the objects is occurred. For 3.5kg mass in total, the CoM and ZMP has about 1.5cm deviation from the reference value(the center of the body). If more objects are loaded then, the humanoid will fall down in this case.

Figure 5 shows the movement with CoM-ZMP control but the loaded objects are not included in calculation of the humanoid CoM. In this case, there is no means to know the variation of the real CoM, but the real ZMP is changed by the F/T sensors on the Ankle. Thus the CoM-ZMP controller gives wrong results with different control actions. As shown in the figure, the CoM-ZMP moves toward the loaded objects. This is the property of the CoM-ZMP controller in Eq. (5), *i.e.*, the CoM and ZMP are controlled by the relative errors between CoM and ZMP. Most previous results have been focused on this situation and they try

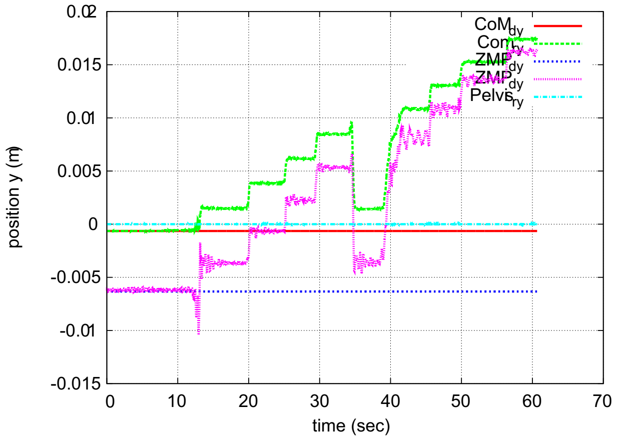

Fig. 4. CoM-ZMP movement with no control in loading objects

to change the reference CoM and/or ZMP to balance the body. For example, the deviation of the CoM and ZMP with and without objects is checked and the deviation is used to modify the reference CoM and ZMP. The modified reference CoM and ZMP is used for control the humanoid. However, it is not so useful when masses are manipulated on both hands with independent motion or loaded and unloaded frequently.

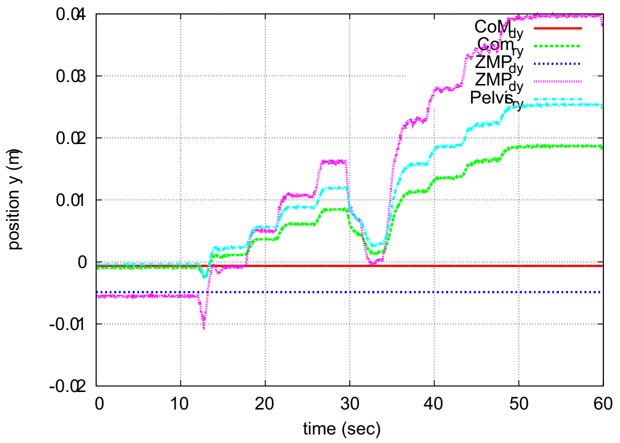

Fig. 5. CoM-ZMP movement with control but no mass augmentation in loading objects

Figure 6 shows the movement with CoM-ZMP control with the mass augmentation. In this case, as shown in the figure, the humanoid moves its body in the opposite direction of the motion without any change of reference CoM and ZMP. The CoM and ZMP are moves within about 5mm and thus the humanoid is in stable state regardless of loading and unloading mass. In order to achieve this stable situation, the pelvis moves about 2cm automatically in the opposite direction of the loaded objects. By using the mass augmentation, the humanoid can be controlled as if there were no additional objects, since the mass effect of external objects is embodied in the humanoid body.

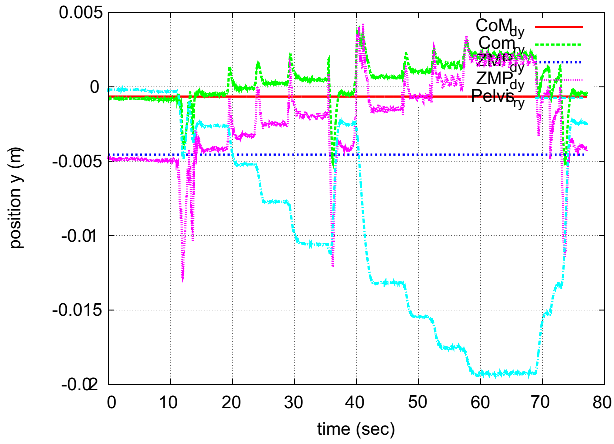

Fig. 6. CoM-ZMP movement with control and mass augmentation in loading objects

V. CONCLUSIONS AND FUTURE WORKS

In this paper, the mass augmentation method is proposed, which is to balance a humanoid when objects are loaded and unloaded dynamically. With the method, without changing the reference CoM and ZMP, the variation of CoM-ZMP due to the loaded objects can be easily and automatically compensated. The results are verified by an initial experiment. In order for more practical usage of the mass augmentation method, more experiments will be performed in the future. For example, when a humanoid is walking with a basket, objects will be loaded to show the effective balancing by the mass augmentation.

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