Whole Body Motion Control Framework for Arbitrarily and Simultaneously Assigned Upper-Body Tasks and Walking Motion

Doik Kim, Bum-Jae You, and Sang-Rok Oh

Abstract. A walking motion of a humanoid has been analyzed or developed without considering motions of the remaining parts of the humanoid. In order to perform tasks in the human's living environment, a walking motion and assigned tasks must be considered at the same time. In this paper, a whole body motion generation method, i.e., the motion embedded CoM Jacobian method is introduced. With the method, a balance control and assigned motions are separated and thus, the assigned motions can be generated without considering balance of a humanoid. As experimental examples, whole body motion of a humanoid is assigned by the teleoperation. Arbitrarily assigned upper body motions and independently generated walking motions are combined to generate a balanced whole body motion with the suggested methods.

1 Introduction

Recently, robot's working places are trying to be extended to the human's daily life. Among various robots, a humanoid is one of the most feasible robots that can survive in the human's living environment. In order to live in the human's living environment, a humanoid should overcome many obstacles such as stairs and furnishings, and understand how to manipulate tools and devices such as many kinds of doors and electric home appliances. All these elemental tasks are also combined to conduct more complicated tasks such as cleaning, cooking, errands, and etc.

For these complicated tasks, a humanoid must have at least two functions: mobility and manipulation. The mobility is one of the most important research topics for a humanoid and many excellent results have been reported in recent years[3]. The manipulation is one of traditional research topics in robotics and has been

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K. Mombaur and K. Berns (Eds.): *Modeling, Simulation and Optimization*, COSMOS 18, pp. 87–98.
DOI: 10.1007/978-3-642-36368-9_7

successfully realized in many real robots. Nowadays, wheeled mobile robots with two arms are popular type for studying manipulation with mobility. This type of robots can handle objects in the human's living environment with less stability problem than a humanoid robot, and thus they can focus on the manipulation with traveling around a working environment.

In order to increase the usefulness of a humanoid, these two research topics, i.e., mobility and manipulation should be coordinated seamlessly with guaranteeing a balance of a humanoid. To achieve the coordination, this paper introduces a whole body motion generation method which resolves the CoM(Center of Mass) Jacobian of a humanoid with given motions of manipulation and mobility. The introduced methods can use almost all manipulation methods without considering balance and walking situation of a humanoid.

This paper is organized as follows: section 2 gives an overview of the resolution of the motion-embedded CoM(MECoM) Jacobian. Section 3 derives the MECoM Jacobin for several cases. Section 4 describes how to use the MECoM Jacobian and shows several applications. Finally, section 5 concludes the paper.

2 Overall System

In order to balance a humanoid with whole body motion, full dynamics or the CoM of whole body is studied usually. The CoM relation is much simpler than full dynamics and thus it is suitable for real implementation. Additionally, the CoM Jacobian gives a relation between the CoM and the joint motion similar to a normal kinematic relation. Consequently, the CoM Jacobian is one of the most simple and efficient whole body motion relations with balancing information. The CoM Jacobian is proposed by Kagami, et al.[5] and formulated analytically by Sugihara, et al.[9]. The dimension of the whole body motion relation is too complicated to be used in real time or with given task motions. If a humanoid has n-dof in total, then the dimension of the CoM Jacobian is $(3 \times n)$. A usual method to solve the CoM Jacobian is that given motions are augmented to the CoM Jacobian as constraints, and finally the joint motions are solved by using an optimization method. The augmentation of given motions increases the overall dimension of the optimization matrix and thus it needs heavy computation with given motions. In order to overcome the defect of the conventional resolution of the CoM Jacobian, the MECoM(Motion-Embedded CoM) Jacobian is proposed[1, 7].

Basic idea of the MECoM Jacobian is that, in most cases, human motions are occurred without considering balance of its body explicitly, and human motions are assigned locally and independently. For example, if a human carries an object with a certain pose, the aim of arms and legs are different, arms are to maintain pose of the object according to the body motion and legs are to walk toward a destination position. While these motions are assigned to corresponding sections, i.e., arms and legs, balance of the whole body is occurred subconsciously. Thus a human needs not consider the balance control of body consciously. This human behavior is applied to control a humanoid with the resolution of the MECoM Jacobian, and consequently, the balancing problem is separated from given motions and furthermore, conventional motion planning methods can be applied without any modification to generate balanced motions.

As shown in Fig. 1, input of the MECoM Jacobian can be divided into two categories: 1) CoM-ZMP control for balance and 2) Motions for given tasks. The CoM-ZMP control algorithms are based on the inverted pendulum model. Many research results on the walking patterns are dealt with this balance algorithms[2, 4, 6]. Motion generation methods have been studied for a long time and mostly, the methods can be categories into the joint motion generation and the Cartesian motion generation.

The output of the MECoM Jacobian is the balanced joint motion of a humanoid, i.e., the MECoM Jacobian distributes the two independent inputs into the whole body joint motion which guarantees balance and given motions as much as possible.

Before developing the motion-embedded CoM Jacobian, a humanoid is divided into several parts. A humanoid has four limbs attached at the main body. Hereafter, each limb and the main body will be called a **section**. For a human, a task is done with some sections, usually two arms, and they balance the body with other sections, usually two legs. It means that not all sections are dedicated into one task, but they do their own tasks, for example, balancing or a given task. Thus it is natural that motions of each section are given independently. According to the existence of a given desired motion, the section is classified into **the idle section** and **the busy section**: the idle section has no given motion and the busy section has a given motion. If a section has zero motion, i.e., it is fixed at current position, it can be considered as an idle section or a busy section. In most case, a supporting section which is attached on the ground are considered as a busy section even if no motion is assigned to, since

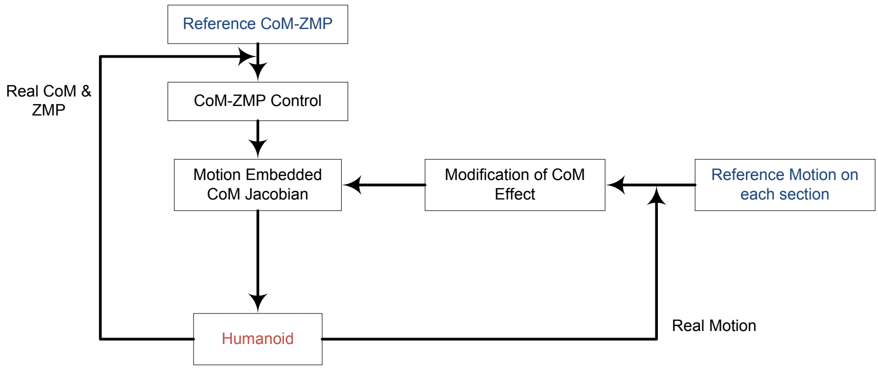

Fig. 1 A basic flow for the resolution of the MECoM Jacobian: balance is maintained by controlling the CoM-ZMP relation, and motions on several sections are given independently. Finally, the balancing control and the given motions are combined by solving the MECoM Jacobian to give balanced motions.

they have a role of balancing the body and thus they should be fixed at the position. Other sections such as arms with zero motion are considered as an idle section if no motion is assigned explicitly.

A given motion of each limb or a main body can be given as a joint motion and/or a Cartesian motion. If a busy section has a motion in the Cartesian space, it will be called **C-busy section** and a section with a motion in the joint space is **J-busy section**.

3 Derivation of Motion-Embedded CoM Jacobian

3.1 CoM Jacobian

This section briefly reviews the CoM Jacobian, and a detail description can be found in [9, 10]. Let us consider a n-DOF humanoid. There are two referential frames to describe a humanoid as shown in Fig. 2. 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 is 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

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

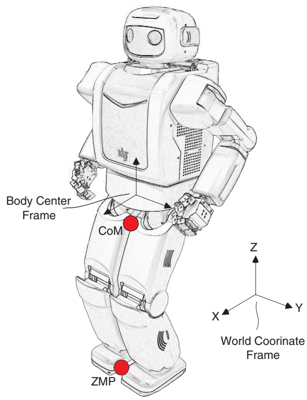

Fig. 2 Coordinate System of Mahru: There are two coordinate systems. The world coordinate frame is to represents the inertial coordinate system and the body center frame is attached on the humanoid body and all the local motions represented with leading superscript ${}^{o}(\cdot)$ are represented based on the body center frame.

We call $\mathbf{J}_G$ the CoM Jacobian hereafter. $\mathbf{p}_G$ is a quite complex function with multiple arguments. Kagami, et al., proposed the numerical method to calculate it[5], which unfortunately needs a large amount of computation. Sugihara, et al., developed a fast and accurate calculation method of $\mathbf{J}_G$ with the following approach[10].

Firstly, the relative CoM velocity with respect to the body center frame, ${}^o\dot{\mathbf{p}}_G$, can be expressed as:

$$ {}^o\dot{\mathbf{p}}_G = \frac{\sum_{i=0}^{n-1} m_i {}^o\dot{\mathbf{r}}_{G_i}}{\sum_{i=0}^{n-1} m_i} = \frac{\sum_{i=0}^{n-1} m_i {}^o\mathbf{J}_{G_i}\dot{\mathbf{q}}}{\sum_{i=0}^{n-1} m_i} \tag{3} $$

where m_i is the mass of link i, ${}^o\mathbf{r}_{G_i}$ is the position of the center of mass of link i with respect to the body center frame, and ${}^o\mathbf{J}_{G_i}$ $(3 \times n)$ is defined by

$$ {}^o\mathbf{J}_{G_i} \equiv \frac{\partial {}^o\mathbf{r}_{G_i}}{\partial \mathbf{q}} \tag{4} $$

Therefore, Jacobian ${}^o\mathbf{J}_G$ which relates $\dot{\mathbf{q}}$ to ${}^o\dot{\mathbf{p}}_G$ is

$$ {}^o\mathbf{J}_G = \frac{\sum_{i=0}^{n-1} m_i {}^o\mathbf{J}_{G_i}}{\sum_{i=0}^{n-1} m_i} \tag{5} $$

Secondly, suppose link 1 is the **base section**, which is fixed in the world frame (for example, when the right leg is the supporting leg, the right leg is fixed on the ground and becomes the base section), the CoM velocity with respect to the world coordinates frame, $\dot{\mathbf{p}}_G$ is

$$ \begin{aligned} \dot{\mathbf{p}}_G =& \dot{\mathbf{p}}_o + \omega_o \times \mathbf{R}_o {}^o\mathbf{p}_G + \mathbf{R}_o {}^o\dot{\mathbf{p}}_G \\ =& \mathbf{R}_o\{{}^o\dot{\mathbf{p}}_G - {}^o\dot{\mathbf{p}}_1 + ({}^o\mathbf{p}_G - {}^o\mathbf{p}_1) \times {}^o\omega_1\} \\ =& \mathbf{R}_o {}^o\mathbf{J}_G\dot{\mathbf{q}} \\ & + \mathbf{R}_o\{-{}^o\mathbf{J}_{\mathbf{v}_1} + [({}^o\mathbf{p}_G - {}^o\mathbf{p}_1)\times]{}^o\mathbf{J}\omega_1\}\dot{\mathbf{q}}_1 \end{aligned} \tag{6} $$

where $\mathbf{p}_o$ is the position of the body center, ω_o is the angular velocity of the body center, and $\mathbf{R}_o$ is the attitude matrix of the body center with respect to the world frame. ${}^o\mathbf{p}_1$ is the position of the base section, ${}^o\omega_1$ is the angular velocity of the base section, ${}^o\mathbf{J}_{\mathbf{v}_1}$ is the linear velocity part of the base Jacobian and ${}^o\mathbf{J}_{\omega_1}$ is the angular velocity part of the base Jacobian with respect to the body center frame. $[\mathbf{v}\times]$ means outer-product matrix of a vector $\mathbf{v}$ (3×1). $\dot{\mathbf{q}}_i$ is the joint velocity of section i. Note that the base section can be any section that is fixed on the ground, but here, we assigned the base section with the number 1 without loss of generality.

In order to use Eq. (6) in the following section, it is rewritten here as:

$$ \begin{aligned} \dot{\mathbf{p}}_G =& \sum_{i=1}^{m} \mathbf{R}_o {}^o\mathbf{J}_{G_i}\dot{\mathbf{q}}_i \\ & + \mathbf{R}_o\{-{}^o\mathbf{J}_{\mathbf{v}_1} + [({}^o\mathbf{p}_G - {}^o\mathbf{p}_1)\times]{}^o\mathbf{J}\omega_1\}\dot{\mathbf{q}}_1 \end{aligned} \tag{7} $$

where m is the number of sections.

Now, let us derive the motion-embedded CoM Jacobian from Eq. (7).

3.2 Motion-Embedded CoM Jacobian

3.2.1 Embedment of J-Busy Section

It is easy to embed a joint motion into the CoM Jacobian, since the joint motion can be directly replaced $\dot{\mathbf{q}}_i$ in Eq. (7).

If section j is a J-busy section, Eq. (7) becomes

$$\begin{aligned}
&\dot{\mathbf{p}}_G - \mathbf{R}_o {}^o\mathbf{J}_{G_j}\dot{\mathbf{q}}_j \\
&= \sum_{i=1, i\neq j}^{m} \mathbf{R}_o {}^o\mathbf{J}_{G_i}\dot{\mathbf{q}}_i \\
&+ \mathbf{R}_o\{-{}^o\mathbf{J}_{\mathbf{v}_1} + [({}^o\mathbf{p}_G - {}^o\mathbf{p}_1)\times]{}^o\mathbf{J}\omega_1\}\dot{\mathbf{q}}_1
\end{aligned} \tag{8}$$

The second term of the left hand side compensates the motion of the jth section. Therefore, the other sections shown in the right hand side can generate a joint motion with the compensated CoM motion.

If at least one section, i.e., the base section, is an idle section, then Eq. (8) can compensate motions of the other sections. If all sections are the J-busy section, there is no section to compensate given motions. In this case, an optimization method needs to be applied.

3.2.2 Embedment of C-Busy Section

Let us derive the motion-embedded CoM Jacobian for the C-busy section. Each section of a humanoid is considered as an independent section, i.e., any section can have its own motion independently without considering other sections. In general, the i-th section has the following relation:

$${}^o\dot{\mathbf{x}}_i = {}^o\mathbf{J}_i\dot{\mathbf{q}}_i \tag{9}$$

where ${}^o\dot{\mathbf{x}}_i = [{}^o\dot{\mathbf{p}}_i^T; {}^o\omega_i^T]^T$ is the end point velocity of the section, ${}^o\dot{\mathbf{p}}_i$ and ${}^o\omega_i$ are the linear and the angular velocity, respectively. $\dot{\mathbf{q}}_i$ is the joint velocity, and ${}^o\mathbf{J}_i$ is the usual Jacobian matrix represented in the body center frame.

In our case, the body center is floating, and thus the end point motion about the world coordinate frame is written as follows:

$$\dot{\mathbf{x}}_i = \mathbf{X}_i^{-1}\dot{\mathbf{x}}_o + \mathbf{X}_o {}^o\dot{\mathbf{x}}_i \tag{10}$$

where $\dot{\mathbf{x}}_o = [\dot{\mathbf{p}}_o^T; \omega_o{}^T]^T$ is the velocity of the body center represented in the world coordinate system, and

$$\mathbf{X}_i = \begin{bmatrix} \mathrm{i}_3 & [\mathbf{R}_o {}^o\mathbf{r}_i\times] \\ \mathbf{0}_3 & \mathrm{i}_3 \end{bmatrix} \tag{11}$$

is a (6×6) matrix which relates the body center velocity and the end point velocity of the i-th section. i_3 and $\mathbf{0}_3$ are the (3×3) identity and zero matrix, respectively.

$\mathbf{R}_o$ is the orientation of the body center based on the world coordinate system. ${}^o\mathbf{r}_i$ is the position vector from the body center to the end of the i-th section based on the body center frame. The transformation matrix $\mathbf{X}_o$ is

$$\mathbf{X}_o = \begin{bmatrix} \mathbf{R}_o & \mathbf{0}_3 \\ \mathbf{0}_3 & \mathbf{R}_o \end{bmatrix}. \tag{12}$$

By combining Eq. (9) and Eq. (10), the end point velocity based on the world coordinate system is

$$\dot{\mathbf{x}}_i = \mathbf{X}_i^{-1}\dot{\mathbf{x}}_o + \mathbf{X}_o{}^o\mathbf{J}_i\dot{\mathbf{q}}_i \tag{13}$$

For simplicity, we will use the relation $\mathbf{J}_i = \mathbf{X}_o{}^o\mathbf{J}_i$, hereafter.

From Eq. (13), we can see that all sections should satisfy the compatibility condition, i.e., *the body center velocity,* $\dot{\mathbf{x}}_o$, *in Eq.* (13) *for each section is the same, so that sections are connected without being broken.*, and thus arbitrary two sections, for example, the i-th and j-th section should satisfy the following relation:

$$\mathbf{X}_i(\dot{\mathbf{x}}_i - \mathbf{J}_i\dot{\mathbf{q}}_i) = \mathbf{X}_j(\dot{\mathbf{x}}_j - \mathbf{J}_j\dot{\mathbf{q}}_j). \tag{14}$$

From Eq. (14), the joint velocity of any section can be represented by the joint velocity of any other section. However, all sections will be represented by the base section, since the motion of the body center is represented by the base section, as shown in Eq. (7). The base section can be the supporting leg in the single supporting phase or one of both legs in the double supporting phase if a humanoid is standing. Let us express the base section with the subscript 1, then the joint velocity of any section is expressed as:

$$\dot{\mathbf{q}}_i = \mathbf{J}_i^{-1}\dot{\mathbf{x}}_i - \mathbf{J}_i^{-1}\mathbf{X}_{i1}(\dot{\mathbf{x}}_1 - \mathbf{J}_1\dot{\mathbf{q}}_1), \tag{15}$$

for $i = 2, \cdots, m$, where m is the number of sections. Here,

$$\mathbf{X}_{i1} = \begin{bmatrix} \mathrm{i}_3 & [\mathbf{R}_o({}^o\mathbf{r}_i - {}^o\mathbf{r}_1)\times] \\ \mathbf{0}_3 & \mathrm{i}_3 \end{bmatrix}. \tag{16}$$

Note that if a section is a redundant system, any null space optimization scheme can be added in Eq. (15), and $\mathbf{J}_i^{-1}$ becomes a generalized inverse.

By substituting Eq. (15) into Eq. (7), the motion-embedded CoM Jacobian relation becomes

$$\begin{aligned} \dot{\mathbf{p}}_G = \; & \mathbf{R}_o\{-{}^o\mathbf{J}_{\mathbf{v}_1} + [({}^o\mathbf{p}_G - {}^o\mathbf{p}_1)\times]{}^o\mathbf{J}_{\omega_1}\}\dot{\mathbf{q}}_1 \\ & + \sum_{i=1}^{m} \mathbf{R}_o{}^o\mathbf{J}_{G_i}\mathbf{J}_i^{-1}(\dot{\mathbf{x}}_i - \mathbf{X}_{i1}\dot{\mathbf{x}}_1) \\ & + \sum_{i=1}^{m} \mathbf{R}_o{}^o\mathbf{J}_{G_i}\mathbf{J}_i^{-1}\mathbf{X}_{i1}\mathbf{J}_1\dot{\mathbf{q}}_1 \end{aligned} \tag{17}$$

where $\mathbf{J}_{\mathbf{v}_1} = \mathbf{R}_o{}^o\mathbf{J}_{\mathbf{v}_1}$ and $\mathbf{J}\omega_1 = \mathbf{R}_o{}^o\mathbf{J}\omega_1$ are the linear and angular velocity part of the base section Jacobian. Note that if $i = 1$, $\dot{\mathbf{x}}_i - \mathbf{X}_{i1}\dot{\mathbf{x}}_1 = \mathbf{0}$ and $\mathbf{R}_o{}^o\mathbf{J}_{G_i}\mathbf{J}_i^{-1}\mathbf{X}_{i1}\mathbf{J}_1\dot{\mathbf{q}}_1 = \mathbf{R}_o{}^o\mathbf{J}_{G_i}\dot{\mathbf{q}}_1$.

Finally, all desired motions, $\dot{\mathbf{x}}_i$, are embedded in the modified CoM Jacobian. Thus the effect of the CoM movement generated by the desired motion is compensated by base section. Eq. (17) can be rewritten like the usual kinematic Jacobian of the base section:

$$\dot{\mathbf{p}}_{\text{meG}} = \mathbf{J}_{\text{meG}}\dot{\mathbf{q}}_1 \tag{18}$$

where

$$\dot{\mathbf{p}}_{\text{meG}} = \dot{\mathbf{p}}_G - \sum_{i=1}^{m} \mathbf{R}_o{}^o\mathbf{J}_{G_i}\mathbf{J}_i^{-1}(\dot{\mathbf{x}}_i - \mathbf{X}_{i1}\dot{\mathbf{x}}_1), \tag{19}$$

$$\begin{aligned}\mathbf{J}_{\text{meG}} = {} & \mathbf{R}_o\{-{}^o\mathbf{J}_{\mathbf{v}_1} + [({}^o\mathbf{p}_G - {}^o\mathbf{p}_1)\times]{}^o\mathbf{J}\omega_1\} \\ & + \sum_{i=1}^{m} \mathbf{R}_o{}^o\mathbf{J}_{G_i}\mathbf{J}_i^{-1}\mathbf{X}_{i1}\mathbf{J}_1.\end{aligned} \tag{20}$$

The modified CoM motion, $\dot{\mathbf{p}}_{\text{meG}}$, consists of two relations: a desired CoM motion(the first term) and the relative effect of motions of each section(the second term). The modified CoM Jacobian, $\mathbf{J}_{\text{meG}}$ also consists of two relations: the effect of the body center(the first term) and the effect of motions of each section(the second term).

The modified CoM Jacobian $\mathbf{J}_{\text{meG}}$ is a $(3 \times n_1)$ matrix where n_1 is the dimension of the base section, which is smaller than that of the original CoM Jacobian. For example, Mahru in Fig. 2 has a 6-dof leg, and thus $n_1 = 6$ if the leg is the base section. After solving Eq. (18), the joint motion of the base section is obtained. The resulting base section motion balances a humanoid robot automatically during the movement of all other sections. With the resulting joint motion of the base section, the joint motion of all other sections are obtained by Eq. (15). The resulting motion follows the desired motion, regardless of the balancing motion of the base section.

4 Application of MECoM Jacobian

4.1 Embedment of a Motion into MECoM Jacobian

As shown in the previous section, there is no difference between manipulation of arms and walking of legs. They are just categorized which type of motion is assigned to a certain section. Currently all sections can have any type of motions, but the base section must have the Cartesian motion, which is usually the zero motion i.e., fixed on the ground. Within the MECoM framework, all motions including walking motion are considered as manipulation or motion with constraints, and the balance is guaranteed by the CoM-ZMP controllers, and finally all these manipulation and balancing results are reflected on the base section.

The balance control focuses on CoM-ZMP controllers, i.e., by changing the CoM-ZMP controller, more stable motion can be obtained without considering given motions. The balance control is tightly related to the CoM-ZMP pattern generation.

According to given motions, the motion embedded CoM Jacobian has two different forms as shown in the previous section: if a given motion is a joint motion, Eq. (8) is used, i.e., the given motion is just replaced. If a given motion is a Cartesian motion, Eq. (15) is used, i.e., the joint motion is obtained from inverse kinematics relation between the given Cartesian motion and the base section.

Consequently, by changing motion generation methods represented in Eq. (15) explicitly or by substituting the results of motion generation methods into Eq. (8) implicitly, we can have more sophisticated motion of a humanoid.

In order to show the replacement of motion generation algorithms, let us consider that a humanoid has arms with more than 6-dof, i.e., arms are redundant. A given desired arm motion is $\dot{\mathbf{x}}_{d_i}$ for the ith section, then we can embed this motion into the MECoM with two methods as follows: Firstly, the given motion is pre-calcuated before embedding into the MECoM Jacobian

$$\dot{\mathbf{q}}_{d_i} = \mathbf{J}_i^{\dagger}\dot{\mathbf{x}}_{d_i} \tag{21}$$

where $(\cdot)^{\dagger}$ represents the pseudo-inverse, and the null vector related part is not included in the equation, but it can be easily added in the equation. With this equation, a desired joint motion, $\dot{\mathbf{q}}_{d_i}$ can be obtained and it is embedded into the MECoM Jacobian as a joint motion with Eq. (8). This joint motion embedment is cascaded with the MECoM Jacobian and thus motion generation algorithms are separated perfectly and it can be developed independently as in Eq. (21).

The second method is that the given motion $\dot{\mathbf{x}}_{d_i}$ is embedded explicitly with Eq. (15) as follows:

$$\dot{\mathbf{q}}_i = \mathbf{J}_i^{\dagger}\dot{\mathbf{x}}_{d_i} - \mathbf{J}_i^{\dagger}\mathbf{X}_{i1}(\dot{\mathbf{x}}_1 - \mathbf{J}_1\dot{\mathbf{q}}_1) \tag{22}$$

Note that the null vector related part also can be included in the equation. Eq. (15) in the previous section must be replaced by Eq. (22) and then the final form of the MECoM Jacobian relation is also changed according to the motion generation method as in Eq. (22). This Cartesian motion embedment is an explicit embedment of given motions and the MECoM Jacobian resolution has all the motion generation routines and we don't need additional motion generation routines in this case.

We can develop or use a new motion generation method to perform a certain task without any modification or consideration of the balance of the body as in Eq. (21) and Eq. (22). The following section will show several applications of the resolution of the MECoM Jacobian.

4.2 Applications

As shown in Fig. 2, the MECoM Jacobian method is applied to the humanoid, **Mahru**, developed at the Cognitive Robotics Center, KIST in 2004. Mahru has the height of about 150cm, and the weight is about 67kg. It has 6-dof for each legs and arms, 1-dof for the waist, 2-dof for the neck, and each hand has 4-dof. In total, it has 35-dof.

4.2.1 Tele-Operation

A humanoid has many degrees-of-freedom, and thus it is hard to control its whole body in real time. To overcome these difficulties, we developed a tele-operation system. In order for the portability, we used a motion capture suit, and human motions are captures from it. The captured motions are interpreted into the humanoid motions, and it is transferred to the humanoid.

As indicated in the section 3.2, we can assign independent motions to each section of the humanoid. For a human-like motion, the upper part of the humanoid is controlled by the joint motion. For stability, the lower part of the humanoid is controlled by the Cartesian motion. From foot-prints of the lower part, the CoM-ZMP pattern is calculated. Consequently, we can assign whole body motion and reference CoM-ZMP for the balance to the humanoid in real time, as shown in Fig. 3. A detail explanation on this application can be found in [8].

Fig. 3 Teleoperation with mixed given motion: The upper body of the humanoid has a joint motion comes from the motion capture suit and the lower body of the humanoid has a Cartesian motion which represents the foot print. Two different input motions are combined with the MECoM Jacobian. The lower body of the humanoid has delayed by about two steps because of the detection procedure of the human walking motion.

4.2.2 Door Opening

In order to interact with an object in the environment, we added a force control algorithm to the upper body motion generation routine. A compliant motion is generated from the force sensor attached on the wrist, and this motion is combined with the captured motion. The final joint motions are embedded into the MECoM Jacobian routine with Eq. (8). The combination of the compliant motion and the captured motion is pre-calculated before embedding. Fig. 4 shows that the humanoid, Mahru, opens a door with given tele-operated motions and force controlled motion.

Fig. 4 Teleoperation with force control: In order to open a door, we embedded a compliance control algorithm into the upper body motion. By doing this, the embedded motion can follow the captured motion and can interact with an object in the environment simultaneously.

5 Concluding Remarks

In this paper, the resolution of the motion embedded CoM Jacobian is introduced as a whole-body motion generation method. In order for a humanoid to survive in the human's daily life, a whole body motion generation method will be critical and the MECoM Jacobian method is suggested as one of promising methods. With the MECoM Jacobian method, a walking motion is also a type of manipulation and it can be handled as a usual motion generation method. The supporting leg or the base section is the only part that is dedicated to the balance of the whole body and it is affected by the balance control which is separated from given motions. Most conventional motion generation methods can be embedded seamlessly as a joint motion or a Cartesian motion into the MECoM Jacobian method. By dividing a complicated whole-body motion generation problem into several independent problems such as a balance control problem and a motion generation problem, it is possible to perform complicated tasks as shown in section 4.

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