2010 IEEE International Conference on Robotics and Automation
Anchorage Convention District
May 3-8, 2010, Anchorage, Alaska, USA

Identification of Flying Humanoids and Humans

Ko Ayusawa, Gentiane Venture and Yoshihiko Nakamura

***Abstract*— The mass properties are important to control robot dynamics or study human dynamics. In our previous works, we proposed a method to identify inertial parameters of legged mechanisms from base-link dynamics, using generalized coordinates and external forces information. In this paper, we propose an identification method based on floating-base dynamics, when the system has no external force. Inertial parameters can be identified without force measurement, only from motion data. The method has been tested on two examples; a simple chain consisted of two links and the human body dynamics.**

I. INTRODUCTION

Dynamics of humanoid robots is characterized by the absence of the link fixed in the inertia frame. When the robot has no external reaction force through the interaction with the environment, for example while jumping or flying, the following dynamics constraint exists; the generalized force which actuates 6 DOFs of the base-link of the robot is always zero. As this constraint is related to the conservation of angular momentum which means a nonholonomic constraint, legged systems enter the category of underactuated mechanisms, and the control and motion planning of such systems have been an active area of research in robotics[1], [2]. In order to discuss the motion arisen from the nonholonomic constraint, we cannot separate the motion from its dynamics; the base-link is forced to move according to the whole body dynamics because of the absence of the generalized force. Because of the nonholonomic property, the motion can excite all the dynamics of the system even under the dynamics constraint. In this paper we address the following issue; *is it possible to identify the whole body dynamics only from the motion data without force measurements?*

The equations of motion of multibody systems can be written in a linear form with respect to the inertial parameters[3], [4], [5]. To identify the inertial parameters, it is normally required to access not only information about motion but also force information such as joint torques and external forces. This paper presents a method to estimate the inertial parameters of free-floating systems only from motion data. Related works are researches about identification of space robots, and they also deal with the identification mainly using motion information. However, they require the parameters of the base body of a space robot and identify only the parameters of the arm and an object handled by a robot[6], or they measure angular momentums of the reaction wheels used for attitude control of the robot[7].

We first prove that the null-space of the regressor matrix, which is the coefficient matrix of the inertial parameters and is composed of generalized coordinates and geometric parameters, is equivalent to the unit vector of inertial parameters. Then, we propose a method to identify the unit vector using the singular value decomposition of the regressor matrix, and show the experimental identification results for two systems, a simple two-link system and the human body.

II. IDENTIFICATION OF FLOATING SYSTEMS USING DYNAMICS CONSTRAINT OF THE BASE-LINK

A. Identification using dynamics of the base-link

The equations of motion of legged systems, composed of n rigid bodies and that has N_J degrees of freedom, are given by Eq.(1).

$$\begin{bmatrix} \boldsymbol{H}_{O1} \, \boldsymbol{H}_{O2} \\ \boldsymbol{H}_{C1} \, \boldsymbol{H}_{C2} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{q}}_0 \\ \ddot{\boldsymbol{q}}_c \end{bmatrix} + \begin{bmatrix} \boldsymbol{b}_O \\ \boldsymbol{b}_C \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{N_c} \begin{bmatrix} \boldsymbol{J}_{Ok}^T \\ \boldsymbol{J}_{Ck}^T \end{bmatrix} \boldsymbol{F}_k^{ext} \tag{1}$$

where,

- $\boldsymbol{H}_{ij} (i = O,\ C,\ j = 1,\ 2)$ is the inertia matrix,
- $\boldsymbol{q_0} \in \boldsymbol{R}^6$ is the generalized coordinates which represents the 6 DOF of the base-link,
- $\boldsymbol{q}_c \in \boldsymbol{R}^{N_J-6}$ is the joint angle vector,
- $\boldsymbol{b}_i$ is the bias force vector including centrifugal, Coriolis and gravity forces,
- $\boldsymbol{\tau} \in \boldsymbol{R}^{N_J-6}$ is the vector of joint torques,
- N_c is the number of contact points with the environment,
- $\boldsymbol{F}_k^{ext} \in \boldsymbol{R}^6$ is the vector of external forces exerted to the system at contact k,
- $\boldsymbol{J}_k \triangleq [\boldsymbol{J}_{Ok} \, \boldsymbol{J}_{Ck}] \in \boldsymbol{R}^{6\times N_J}$ is the basic Jacobian matrix of the position at contact k and of the orientation of the contact link with respect to generalized coordinates.

The upper part of Eq.(1) represents the equations of motion of the base-link, which means the root of the kinematic tree structure. And the lower part represents the equations of motion of the joints. The equations of motion of multibody systems can be written in a linear form with respect to the dynamic parameters[3], [4], and Eq.(2) can be obtained from Eq.(1).

$$\begin{bmatrix} \boldsymbol{Y}_O \\ \boldsymbol{Y}_C \end{bmatrix} \boldsymbol{\phi} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{N_c} \begin{bmatrix} \boldsymbol{J}_{Ok}^T \\ \boldsymbol{J}_{Ck}^T \end{bmatrix} \boldsymbol{F}_k^{ext} \tag{2}$$

This research is supported by Category S of Grant-in-Aid for Scientific Research(20220001), Japan Society for the Promotion of Science

K. Ayusawa and Y. Nakamura are with the Department of Mechano-Informatics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, 113-8656 Tokyo, Japan ayusawa, nakamura@ynl.t.u-tokyo.ac.jp

G. Venture is with the Department of Mechanical System Engineering, The Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, 184-8588 Tokyo, Japan venture@cc.tuat.ac.jp

Where,

- $\boldsymbol{\phi} \in \boldsymbol{R}^{10n}$ is the vector of constant inertial parameters such that

$$\boldsymbol{\phi} = \left[\, \boldsymbol{\phi}_0^T \;\; \boldsymbol{\phi}_1^T \;\cdot\cdot\; \boldsymbol{\phi}_{n-1}^T \,\right]^T \tag{3}$$

- $\boldsymbol{\phi}_j \in \boldsymbol{R}^{10}$ is the vector of constant inertial parameters of link j,

$$\begin{aligned} \boldsymbol{\phi}_j = [\; & m_j \;\; ms_{j,x} \;\; ms_{j,y} \;\; ms_{j,z} \;\; I_{j,xx} \\ & I_{j,yy} \;\; I_{j,zz} \;\; I_{j,yz} \;\; I_{j,zx} \;\; I_{j,xy} \;]^T \end{aligned} \tag{4}$$

- m_j is the mass of the link j,
- $I_{j,xx}$, $I_{j,yy}$, $I_{j,zz}$, $I_{j,yz}$, $I_{j,zx}$, $I_{j,xy}$ are the 6 independent components of the inertia matrix $\boldsymbol{I}_j$ expressed in the frame attached to link j,
- $s_{j,x}$, $s_{j,y}$, $s_{j,z}$ are the components of the vector $\boldsymbol{s}_j$, the center of mass with respect to the origin of the frame attached to link j.
- $\boldsymbol{Y} \triangleq [\boldsymbol{Y}_O^T \; \boldsymbol{Y}_C^T]^T \in \boldsymbol{R}^{N_J \times 10n}$ is the regressor matrix or regressor, which is composed of $\boldsymbol{q}_0$, $\boldsymbol{q}_c$, their derivatives, and geometric parameters like length of each link. The method to obtain $\boldsymbol{Y}$ is shown in [4].

Only the minimal set of inertial parameters that describes the dynamics of the system can be identified. This minimal set is called base parameters. It is computed symbolically or numerically from the inertial parameters $\boldsymbol{\phi}$ by eliminating those that have no influence on the model and regrouping some according to the kinematics of the system[8], [9]. The minimal identification model given by Eq.(5) is thus obtained.

$$\begin{bmatrix} \boldsymbol{Y}_{OB} \\ \boldsymbol{Y}_{CB} \end{bmatrix} \boldsymbol{\phi}_B = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau} \end{bmatrix} + \sum_{k=1}^{N_c} \begin{bmatrix} \boldsymbol{J}_{Ok}^T \\ \boldsymbol{J}_{Ck}^T \end{bmatrix} \boldsymbol{F}_k^{ext} \tag{5}$$

where,

- N_B is the number of the base parameters,
- $\boldsymbol{\phi}_B \in \boldsymbol{R}^{N_B}$ is the vector of the base parameters,
- $\boldsymbol{Y}_B \triangleq [\boldsymbol{Y}_{OB}^T \; \boldsymbol{Y}_{CB}^T]^T \in \boldsymbol{R}^{N_J \times N_B}$ is called the regressor matrix for the base parameters.

Most common identification methods use Eq.(5) to identify $\boldsymbol{\phi}_B$, we have proposed to use only the upper-part of the identification model Eq.(5), the equations of motion of the base-link[10].

$$\boldsymbol{Y}_{OB} \boldsymbol{\phi}_B = \boldsymbol{F}^{ext} \tag{6}$$

Where $\boldsymbol{F}^{ext} \triangleq \sum_{k=1}^{N_c} \boldsymbol{J}_{Ok}^T \boldsymbol{F}_k^{ext}$ denotes the contribution of the external forces. Using the identification model given by Eq.(5) or the model given by Eq.(6) leads to similarly identify the base parameters $\boldsymbol{\phi}_B$. However, this method stands only if the reduction of the system to these six equations keeps unchanged the number of parameters that are structurally identifiable with the whole system. We have mathematically proven that the reduced system Eq.(6) leads to similarly identify the whole set of base parameters[11]. When using Eq.(5), it is necessary to measure the joint angles $\boldsymbol{q}_c$, the generalized coordinates $\boldsymbol{q}_0$, the contact forces $\boldsymbol{F}_k^{ext}$ at contact k, and the joint torque $\boldsymbol{\tau}$. However, it is also necessary to take into account the non-linear internal components such as friction and viscosity of the joints. The modeling of these elements is still an open problem. In conventional methods using Eq.(5), the identified inertial parameters are thus contaminated by the inaccuracies in these models. These issues are eliminated when using the base-link approach given in Eq.(6). The feature of Eq.(6) is that the generalized force which actuates 6 DOFs of the base-link is always zero, and Eq.(6) does not contain the joint torque $\boldsymbol{\tau}$ or non-linear internal components such as friction and viscosity. Consequently to estimate the set of base parameters $\boldsymbol{\phi}_B$, the measurement of the joint torque for each joint is not required. Only measurement of the contact forces, the joint angles, and the generalized coordinates are required. This method has shown to be of benefit for legged systems such as humanoid robots and humans[10].

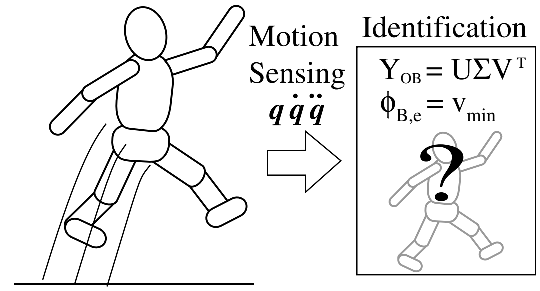

Fig. 1. Conceptual diagram of proposed identification method based on free-base dynamics

B. Identification model of the floating base-link

When no external force acts on the legged system, for example when the system is jumping or flying, is it possible to identify the whole set of base parameters? In this sub-section, we discuss whether the whole parameters of a floating system can be identified using only the equations of motion of the base-link.

The equations of motion of the base-link without external forces can be written as follow.

$$\boldsymbol{Y}_{OB} \boldsymbol{\phi}_B \;\;=\;\; \boldsymbol{0} \tag{7}$$

The right-hand side of Eq.(7) is always zero because of the dynamics constraint. In Eq.(7) there exists the constant vector $\boldsymbol{\phi}_B$ in this linear equation. Thus the vector-space $\mathrm{V}(\boldsymbol{Y}_{OB})$ spanned by the functional column vectors of $\boldsymbol{Y}_{OB}$ is not linear independent, and we have

$$\dim \mathrm{V}(\boldsymbol{Y}_{\mathrm{OB}}) \;\;\leq\;\; N_B - 1 \tag{8}$$

We assume some systems whose dimension number of $\mathrm{V}(\boldsymbol{Y}_{OB})$ obtained from exciting motions decreases by only one, which means

$$\dim \mathrm{V}(\boldsymbol{Y}_{\mathrm{OB}}) \;\;=\;\; N_B - 1 \tag{9}$$

Given this assumption, the basis of the null space of $\mathrm{V}(\boldsymbol{Y}_{OB})$ is only one vector, and equal to $\boldsymbol{\phi}_{B,e} = \frac{\boldsymbol{\phi}_B}{|\boldsymbol{\phi}_B|}$. We can identify the unit vector $\boldsymbol{\phi}_{B,e}$ from the dynamics constraint of the base-link, the null space of $\mathrm{V}(\boldsymbol{Y}_{OB})$. If we want to identify the vector $\boldsymbol{\phi}_B$, we thus need to measure the norm of the vector.

Under the assumption that the decrease of the dimension of $\mathrm{V}(\boldsymbol{Y}_{OB})$ caused by the dynamics constraint of the base-link is only one, the unit vector of the base parameters can be identified only from motion data, i.e. without force information. In order to identify the normal base parameters, we need at least one base parameter, for example the total mass of the system. In other word, we can measure only subjective force information of the system, which lacks objective information, i.e. unit system of force. We measure no torque information in this method, however, we can also collect objective information if we use at least one force sensor mounted on the system.

In the field of the identification of space robots, Murotsu et al.[6] proposed a method for dynamics identification of an object handled by a space robot. They divide the system into two groups, one is the base body system of the space robot whose parameters are known, and the other is the arm and object body system whose parameters are unknown. And they identify the unknown parameters from the known dynamics. In the sense of using known parameters, our method is similar to theirs. However we can identify the unit vector of the base parameters without known parameters or force information. If we want to identify the normal base parameters, we need not divide the system and can identify from at least one known base parameter.

C. Identification of unit vector of inertial parameters using singular value decomposition method

In this sub-section, we present the method to identify the unit vector $\boldsymbol{\phi}_{B,e}$ from the null space of vector space $\mathrm{V}(\boldsymbol{Y}_{OB})$ derived from Eq.(7).

Actually for the identification, we have to calculate the regressor matrices at every sampling time from the measured motion information such as generalized coordinates and their derivatives. Then we arrange the sampled regressors at $t = t_1, t_2 \cdots$ lengthwise, and compose a large regressor matrix $\boldsymbol{Y}_{all}$ and a large vector of forces $\boldsymbol{F}_{all}$.

$$\boldsymbol{Y}_{all} \triangleq \begin{bmatrix} \boldsymbol{Y}_{OB,t_1} \\ \boldsymbol{Y}_{OB,t_2} \\ \vdots \end{bmatrix} \tag{10}$$

$$\boldsymbol{F}_{all} \triangleq \begin{bmatrix} \boldsymbol{F}^{ext}{}_{,t_1} \\ \boldsymbol{F}^{ext}{}_{,t_2} \\ \vdots \end{bmatrix} \tag{11}$$

In Eq.(7), $\boldsymbol{F}^{ext}$ is always $\boldsymbol{0}$, thus $\boldsymbol{F}_{all} = \boldsymbol{0}$. We obtain Eq.(12).

$$\boldsymbol{Y}_{all}\boldsymbol{\phi}_{B,e} = \boldsymbol{0} \tag{12}$$

From this identification model Eq.(12), we calculate the null space of the regressor $\boldsymbol{Y}_{all}$. However, the measured regressor includes some errors of measured motion data and kinematic modeling. We define $\Delta\boldsymbol{Y}_{all}$ as error of the regressor, and $\widehat{\boldsymbol{Y}}_{all}$ as the measured regressor.

$$\widehat{\boldsymbol{Y}}_{all} = \boldsymbol{Y}_{all} + \Delta\boldsymbol{Y}_{all} \tag{13}$$

The singular value decomposition[12] of the measured regressor $\widehat{\boldsymbol{Y}}_{all}$ is represented by

$$\widehat{\boldsymbol{Y}}_{all} = \begin{bmatrix} \boldsymbol{U}\ \boldsymbol{u}_{min} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Sigma} & \boldsymbol{0} \\ \boldsymbol{0}^T & \sigma_{min} \end{bmatrix} \begin{bmatrix} \boldsymbol{V} & \boldsymbol{v}_{min} \\ \boldsymbol{v}^T & v_{min} \end{bmatrix}^T \tag{14}$$

Then, we identify the singular vector corresponding to the smallest singular value σ_{min} as the estimated unit vector $\widehat{\boldsymbol{\phi}}_{B,e}$.

$$\widehat{\boldsymbol{\phi}}_{B,e} = \begin{bmatrix} \boldsymbol{v}_{min} \\ v_{min} \end{bmatrix} \tag{15}$$

If the singular vector corresponding to σ_{min} is chosen as the solution of Eq.(12) as above, this solution minimizes the Frobenius norm $||\Delta\boldsymbol{Y}_{all}||_F$, where $\Delta\boldsymbol{Y}_{all}$ is the error of the regressor. Then, $\boldsymbol{Y}_{all}$ is given by Eq.(12), and the error norm $||\Delta\boldsymbol{Y}_{all}||_F = \sigma_{min}$.

$$\boldsymbol{Y}_{all} = \begin{bmatrix} \boldsymbol{U}\ \boldsymbol{u}_{min} \end{bmatrix} \begin{bmatrix} \boldsymbol{\Sigma} & \boldsymbol{0} \\ \boldsymbol{0}^T & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{V} & \boldsymbol{v}_{min} \\ \boldsymbol{v}^T & v_{min} \end{bmatrix}^T \tag{16}$$

This method can be seen as a kind of total least square method[12]. The solution of usual total least square method satisfies Eq.(12), and minimizes the Frobenius norm of the augmented matrix $[\Delta\boldsymbol{Y}_{all}\ \ \Delta\boldsymbol{F}_{all}]$, where $\Delta\boldsymbol{F}_{all}$ is the error of the external force $\boldsymbol{F}_{all}$. In this paper, we obtain $\boldsymbol{F}_{all}$ from the dynamics constraint of the base-link. It means that there is no error of force information; $\Delta\boldsymbol{F}_{all} = \boldsymbol{0}$, as $\boldsymbol{F}_{all} = \boldsymbol{0}$ and we are not measuring $\boldsymbol{F}_{all}$.

The conceptual diagram of this identification method is presented in Fig.1. The following is a summary. This method only requires the motion data while the system has no external forces, for example when the system is jumping or flying. The unit vector of base parameters $\boldsymbol{\phi}_{B,e}$ can be calculated as the smallest singular vector of the regressor matrix $\boldsymbol{Y}_{all}$. If we want to identify the vector $\boldsymbol{\phi}_B$, we need to measure at least one base parameter, for example the total mass of the system.

III. Experimental results of identification

The proposed method is tested with two systems, and the experimental results are presented in this section. We note that this method is based on the assumption that dimension number of the regressor of a floating base-link decreases by only one. It can possibly decrease by more than one, for example, when the system is made of only one link, or when there is an end-link connected with a rotational joint and center of mass of the end-link is located directly on the joint axis. However, if the system has only rotational or spherical joints and each center of mass is obviously not located on each joint axis, we can generally assume that the decrease of the dimension is only one.

A. Identification of two links connected with a rotational joint

First, in this sub-section we show the identification results of a simple two-link system as shown in Fig.2. Two links are connected with a single rotational joint, which has no actuator and whose axis is simply supported by bearings.

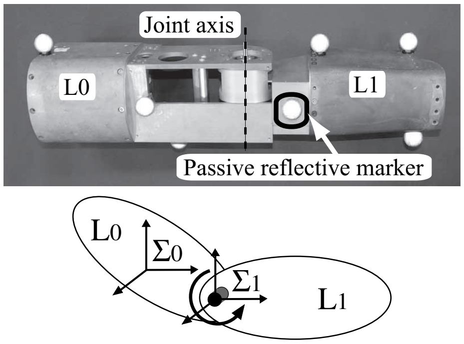

Fig. 2. The kinematic chain consisted of two links connected with a rotational joint

For identification, we threw the links into the air several times, and recorded the motion data in the air. To measure the motion of the links we used a motion capture system. The links are equipped with optical markers as shown in Fig.2, and their motion is captured by 10 cameras every 5 ms, and totally recorded for about 20 seconds. From the measured position of markers, the generalized coordinates $\boldsymbol{q}_0$ of the base-link and the joint angle $\boldsymbol{q}_c$ can be computed. The data of $\boldsymbol{q}_0$ and $\boldsymbol{q}_c$ is low-pass filtered to remove noise with a zero-phase forward and reverse Butterworth filter with an order 3 and a cut-off frequency of 10[Hz] that is enough higher than the frequency of the dynamics of the captured motion. The derivatives $\dot{\boldsymbol{q}}_0$, $\dot{\boldsymbol{q}}_c$, $\ddot{\boldsymbol{q}}_0$, $\ddot{\boldsymbol{q}}_c$ can be also obtained numerically. Then, we can compute $\boldsymbol{Y}_{all}$ using those variables and kinematic parameters of the system at every sampling time.

This system has two links and one rotational joint. The base parameters $\boldsymbol{\phi}_B = [{\boldsymbol{\phi}_{B0}}^T\ {\boldsymbol{\phi}_{B1}}^T]^T$ of this system can be computed[8] as below,

TABLE I

IDENTIFICATION RESULTS WITH EXPERIMENTAL DATA WHEN THE CHAIN CONSISTED OF TWO LINKS CONNECTED WITH A ROTATIONAL JOINT IS FLYING FREELY WITHOUT EXTERNAL FORCES

Link ID	name	Measured parameter	Identified parameter
L0	M[kg]	0.997	0.997
	MC_x[kgm]	0.000	-0.002
	MC_y[kgm]	0.064	0.064
	MC_z[kgm]	0.006	0.003
	J_{xx}[kgm^2]	0.013	0.006
	J_{yy}[kgm^2]	0.008	0.003
	J_{zz}[kgm^2]	0.019	0.017
	J_{yz}[kgm^2]	0.000	0.003
	J_{xz}[kgm^2]	0.000	0.003
	J_{xy}[kgm^2]	0.000	0.000
L1	mc_x[kgm]	-0.036	-0.029
	mc_y[kgm]	-0.003	-0.006
	$I_{xx}-I_{yy}$[kgm]	-0.005	-0.008
	I_{zz}[kgm^2]	0.006	0.001
	I_{yz}[kgm^2]	0.000	-0.004
	I_{xz}[kgm^2]	0.000	0.001
	I_{xy}[kgm^2]	0.000	-0.001

- $\boldsymbol{\phi}_{B0} \in \boldsymbol{R}^{10}$ is the vector of base parameters of the base-link $L0$ of the system.

$$\boldsymbol{\phi}_{B0} = [\ M_0\ \ MS_{0,x}\ \ MS_{0,y}\ \ MS_{0,z}\ \ J_{0,xx}\ \ J_{0,yy}\ \ J_{0,zz}\ \ J_{0,yz}\ \ J_{j,zx}\ \ J_{j,xy}\ ]^T \tag{17}$$

- $\boldsymbol{\phi}_{B1} \in \boldsymbol{R}^7$ is the vector of base parameters of the other side link $L0$.

$$\boldsymbol{\phi}_j = [\ ms_{1,x}\quad ms_{1,y}\quad I_{1,xx}-I_{1,zz}\quad I_{1,zz}\quad I_{1,yz}\quad I_{1,zx}\quad I_{1,xy}\ ]^T \tag{18}$$

- $M_0 = m_0 + m_1$ is the base parameter of L0 representing the mass,
- $\boldsymbol{MS}_0 \in \boldsymbol{R}^3$ is the base parameter of L0 representing the first moment of inertia,

$$\boldsymbol{MS}_0 = m_0\boldsymbol{s}_0 + m_1{}^0\boldsymbol{p}_1 + {}^0\boldsymbol{r}_1 \tag{19}$$

- ${}^0\boldsymbol{r}_1 = {}^0\boldsymbol{R}_1[\ 0\ \ 0\ \ m_1 s_{1,z}\ ]^T$,
- $J_0 \in \boldsymbol{R}^{3\times3}$ is the base parameter of L0 representing the inertia,

$$\boldsymbol{J}_0 = \boldsymbol{I}_0 + m_1[{}^0\boldsymbol{p}_1\times]^T[{}^0\boldsymbol{p}_1\times] + [{}^0\boldsymbol{p}_1\times]^T[{}^0\boldsymbol{r}_1\times] + [{}^0\boldsymbol{r}_1\times]^T[{}^0\boldsymbol{p}_1\times] + I_{1,yy}{}^0\boldsymbol{R}_1 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} {}^0\boldsymbol{R}_1^T \tag{20}$$

- ${}^0\boldsymbol{R}_1$ is the rotation matrix from the frame attached to $L0$ to the frame attached to $L1$,
- ${}^0\boldsymbol{p}_1$ is the translational vector from the frame attached to $L0$ to the frame attached to $L1$,

The identified unit vector $\widehat{\boldsymbol{\phi}}_{B,e}$ of base parameters and the measured unit vector $\boldsymbol{\phi}_{B,e}$ are shown in Table I. In order to obtain $\boldsymbol{\phi}_{B,e}$, we measured the weight of all the components of each link, and calculated center of mass and inertia matrix using CAD. As it can be seen from Table I, the identified parameters are matching with the measured data, especially large inertial parameters such as mass and center of mass. Each absolute error of a parameter is under 0.007, so the parameters have been successfully identified. However, the maximum singular value of the measured regressor matrix is 1191, the smallest singular value is 18, and the second smallest is 76, so the second smallest value is near the smallest one. That can be explained not only by measurement errors, numerical computation of derivatives, model errors, and existence of air resistance, but also by the poor excitation property of the motion in the air mainly caused by lack of actuated joint.

B. Identification of human body in the air

In this sub-section, we show the identification results of the human body using only aerial motion data. We consider a model of the human body made of 34 DOF and 15 rigid links[13] as described in Table II. It represents the most important DOF that are used in daily activities like locomotion. In addition to the 34 DOF of its kinematics, 6 DOF are used to define the generalized coordinates. This kinematic model leads to 128 base parameters, and the detail

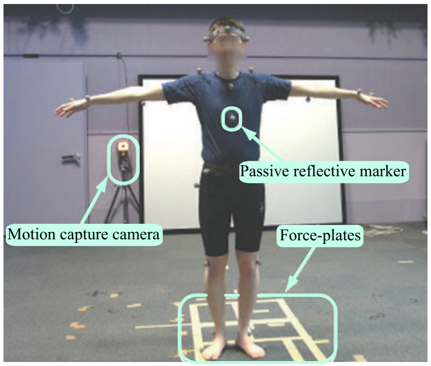

Fig. 3. Experimental set up of the behavior capture systems

of a calculation method of base parameters can be found in [11].

The motion is recorded by an optical motion capture system as referred above. The experimental set up of the capture systems is shown in Fig.3. We use 35 optical markers pasted on the body of the subjects at defined anatomical points to insure accuracy of inverse kinematics computations, and the geometric properties of the kinematics are automatically computed from the markers information. The regressor $\boldsymbol{Y}_{all}$ can be computed from the position of markers in the same way mentioned in the identification of the two-link system. The contact forces are simultaneously measured by two force-plates. This force information is not used for identification, but both to detect the moment in the air and validate the identification results.

For the identification of the unit vector $\widehat{\boldsymbol{\phi}}_{B,e}$, we recorded 4 sets of motion of the subject jumping on the force-plates several times, and extracted the sequences when the subject in the air from the data set. Some snapshots of the motion are shown in Fig.4. As the base parameter of the base-link representing the mass is equivalent to the total mass of the system, we also identify the standard base parameters $\widehat{\boldsymbol{\phi}}_B$ from both $\widehat{\boldsymbol{\phi}}_{B,e}$ and the mass of the subject measured by a scale.

Finally the obtained results are validated. For that, we compare the measured contact forces: $\boldsymbol{F}^{ext}$ (Force-plate data) with the contact forces that are computed using the identified parameters: $\widehat{\boldsymbol{F}}^{ext} = \boldsymbol{Y}_{OB}\widehat{\boldsymbol{\phi}}_B$. Cross validations consist in using motion that is not used for identification in order to evaluate the ability of the model and the identified parameters to predict the generalized forces. We measure some motion using the visualization interface[14] that can provides enough excitation. The generated motion seems like a kind of exercise of the whole body, and is used for the cross validation.The obtained results are presented in Fig.5. They give the comparison of the generalized forces $\boldsymbol{F}^{ext}$ (red thick line) obtained from the force-plates, with the estimated forces $\widehat{\boldsymbol{F}}^{ext}$ (blue thin line) obtained from the identified parameters, for each of the 6 components. The absolute mean error of 6 components is shown in the caption of Fig.5. From the cross-validation figures, the identified parameters allow a good prediction of the generalized forces, and the mean errors are small with respect to the full scale.

TABLE II

CHOSEN DOF IN THE MODEL OF THE HUMAN BODY

name of joint	type of joint	number of DOF
neck	spherical	3
waist	spherical	3
right shoulder	spherical	3
right elbow	revolute	1
right wrist	spherical	3
left shoulder	spherical	3
left elbow	revolute	1
left wrist	spherical	3
right hip	spherical	3
right knee	revolute	1
right ankle	spherical	3
left hip	spherical	3
left knee	revolute	1
left ankle	spherical	3

IV. CONCLUSION

The results in this paper are summarized as follows:

1) We proposed a method to estimate the inertial parameters of free-floating systems. This method makes use of the dynamics constraint of the floating base-link, using motion data and without force information, which means that the identified parameters are unaffected by the measurement error or noise of forces.
2) If the external force acted on the system is always zero, the identification method using external force information[10], [14] cannot be applied. The proposed method can give the solution in such a special case, however it requires at least one dynamics information such as total mass of the system.
3) The method is verified by experiments with a simple two-link system connected with a single rotational joint. The identified parameters are close to the measured parameters, and show the validation of the proposed method.
4) We applied the proposed method to identify the inertial parameters of the human body. Several jumping motions are recorded for identification, and one motion with enough excitation is for cross-validation. To check the validation, the estimated forces from identified parameters are compared with the measured forces, and there is a good correlation with the estimated forces and measured ones. This method can be also applicable to any other legged systems such as humanoid robots, and to space robots.

REFERENCES

[1] Y. Nakamura and R. Mukherjee, "Exploiting nonholonomic redundancy of free-flying space robots," *IEEE Trans. of Robotics and Automation*, vol. 9, no. 4, pp. 499–506, 1993.

[2] S. Dubowsky and E. Papadopoulos, "The kinematics, dynamics, and control of free-flying and free-floating space robotic systems," *IEEE Trans. of Robotics and Automation*, vol. 9, no. 5, pp. 531–543, 1993.

[3] H. Mayeda, K. Osuka, and A. Kanagawa, "A new identification method for serial manipulator arms," in *Proc. IFAC 9th World Congress*, 1984, pp. 74–79.

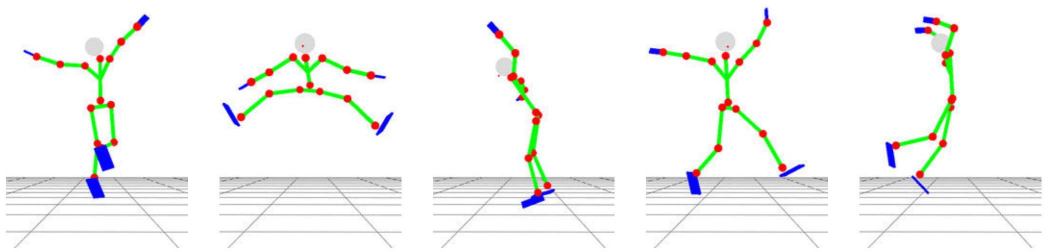

Fig. 4. Snapshots of the jumping motion used for identification.

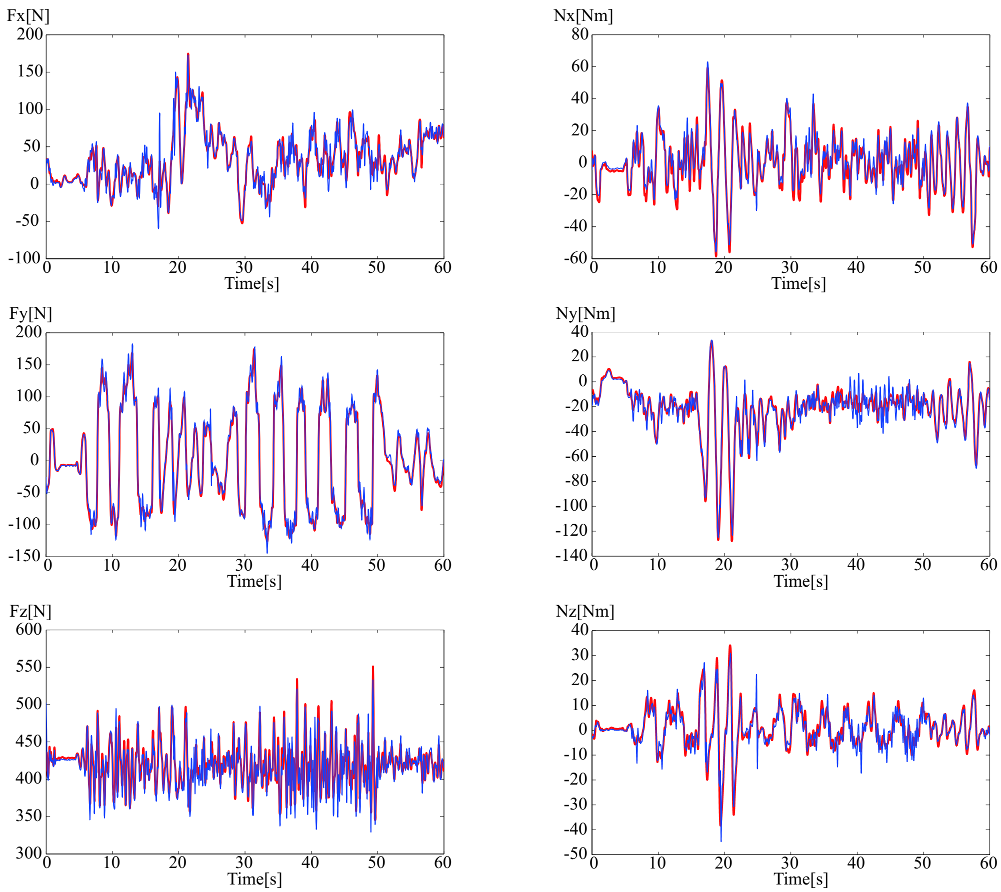

Fig. 5. Cross validation of external forces for the motion exciting whole body from aerial identification result. Red thick lines show the measured forces, and blue thin lines show the estimated forces from identified parameters. Mean errors of 6-axis forces are as follows: Fx 6.38[N], Fy 5.90[N], Fz 7.08[N], Nx 2.86[Nm], Ny 3.47[Nm], Fz 2.12[Nm].

[4] C.G. Atkeson, C.H. An, and J.M. Hollerbach, "Estimation of inertial parameters of manipulator loads and links," *Int. J. of Robotic Research*, vol. 5, no. 3, pp. 101–119, 1986.

[5] W. Khalil and E. Dombre, *Modeling, identification and control of robots*, Hermès Penton, London-U.K, 2002.

[6] Y. Murotsu, K. Senda, M. Ozaki, and S. Tsujio, "Parameter identification of unknown object handled by free-flying space robot," *AIAA J. of Guidance, Control, and Dynamics*, vol. 17, no. 3, pp. 488–494, 1994.

[7] K. Yoshida and S. Abiko, "Inertia parameter identification for a free-flying space robot," in *Proc. of the AIAA Guidance, Navigation, and Control Conference*, 2002, AIAA 2002_4098.

[8] H. Kawasaki, Y. Beniya, and K. Kanzaki, "Minimum dynamics parameters of tree structure robot models," in *Int. Conf. of Industrial Electronics, Control and Instrumentation*, 1991, pp. 1100–1105.

[9] W. Khalil and F. Bennis, "Symbolic calculation of the base inertial parameters of closed-loop robots," *Int. J. of Robotics Research*, vol. 14, no. 2, pp. 112–128, 1995.

[10] K. Ayusawa, G. Venture, and Y. Nakamura, "Identification of humanoid robots dynamics using floating-base motion dynamics," in *Proc. IEEE/Int. Conf. on Intelligent Robot System*, 2008, pp. 2854–2859.

[11] K. Ayusawa, G. Venture, and Y. Nakamura, "Symbolic identifiability of legged mechanism using base-link dynamics," in *IFAC Symposium on System Identification*, 2009, pp. 693–698.

[12] G.H. Golub and C.F. Van Loan, *Matrix Computations*, Johns Hopkins University Press, Baltimore, 1983.

[13] K. Yamane and Y. Nakamura, "Natural motion animation through constraining and deconstraining at will," *IEEE Trans. on Visualization and Computer Graphics*, vol. 9, no. 3, pp. 352–360, 2003.

[14] G. Venture, K. Ayusawa, and Y. Nakamura, "Realtime identification software for human whole-body segment parameters using motion capture and its visualization interface," in *Proc. of the IEEE Int. Conf. on Rehabilitation Robotics*, 2009, pp. 109–114.