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Parameter Identification of Unknown Object Handled by Free-Flying Space Robot

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This paper is concerned with parameter identification methods for inertial parameters of the unknown object handled by manipulators on a free-flying space robot. The parameter identification is necessary for precise control because the payload changes the kinematics of the system together with the dynamics. Two methods are proposed under the condition that the robot is free to translate and rotate. One method is based on the conservation principle of linear and angular momentum and the other on Newton-Euler equations of motion. Only the linear/angular velocities and accelerations of the satellite base are used in the identification methods with no information about the force and torque utilized. The feasibility of the methods is demonstrated by a hardware experiment on the ground as well as numerical simulation.

Introduction

FUTURE space missions will require the construction, repair, and maintenance of space structures on orbit by the use of manipulators mounted on a free-flying satellite vehicle. The on-orbit operation of space robots presents many complicated dynamic problems. One of these problems is the lack of an inertially fixed base on which to mount the space robots, resulting in an interaction between the manipulator dynamics and the dynamics of the satellite.

The kinematics of the space manipulator have been discussed by Vafa and Dubowsky[1] and Umetani and Yoshida.[2] They have proposed a concept of a virtual manipulator and a generalized Jacobian matrix, respectively, taking account of dynamical interactions between the manipulators and the satellite. The virtual manipulator and the generalized Jacobian matrix are computed by using geometric parameters together with inertial parameters of all of the links constructing the space robot, where the inertial parameters are the mass, the mass center, and the inertial tensor. This means that inertial parameters change the kinematics of the space robot. The space robot will sometimes handle objects that will have unknown inertial parameters. Therefore, the kinematics and dynamics of the whole system cannot be predicted when the manipulator grasps an unknown object. Further, when the objects are not grasped in their nominal position and orientation, the computed virtual manipulator and generalized Jacobian matrix have some errors even if the inertial parameters of the grasped objects are known exactly.

Some of the control schemes for rigid space manipulators are proposed by using the generalized Jacobian matrix.[3–6] All of the studies have discussed only the case when the manipulator does not handle any objects. Robust stability of those control schemes has never been verified against the kinematical and dynamical variation, e.g., the unknown object. Therefore, it is very important to estimate the inertial parameters accurately for precise control after the manipulator has grasped the objects.

In this paper, two parameter identification methods are proposed to estimate the unknown inertial parameters of the manipulated objects from the movements of the whole system measured by using the linear and angular velocities and/or acceleration sensors, under the condition that the robot is free to translate and rotate. One identification method is based on the linear and angular momentum conservation law. The feature of the method is to use measurements of the displacements and velocities of joints and the satellite. The other method is based on Newton-Euler equations of motion. Identification methods based on the equations of motion usually use force and torque measurements.[7–10] However, the present method does not use the joint forces and torques, but it uses the linear and angular acceleration of the satellite. The two methods give solutions to an inverse problem of the kinematics computed from the inertial parameters of the manipulated objects. The feasibility of the identification methods is shown by numerical simulations and a hardware experiment on the ground.

Models and Identification Problem

Models of Space Robot and Definitions

A free-flying space robot considered here has a manipulator with n degrees of freedom ($n \geq 2$). This system is a rigid multibody system connected by rotary hinges with no closed-loop chains. An unknown object is grasped firmly by the manipulator hand, and its relative position and orientation to the manipulator hand do not change. For simplicity, only one joint, i.e., joint i, is driven, and the other joints are fixed during the action for identification. Hence the system is considered as a two-body system with two rigid bodies connected by a rotational joint.

Mayeda and Osuka[7] proposed an identification method for serial manipulator arms on the ground that is based on the one-joint-driving motion similar to that in this study. The motion makes the identification method able to estimate a specified group of parameters separately from the other parameters. This study employs the motion just for simplification of formulation because one can treat the whole system as a two-body system. One could use any motions for the identification other than the one-joint-driving motion, if fundamental equations for the parameter identification had been derived from the equation of motion of the whole rigid multibody system with $n + 1$ links in the same manner as those in the following formulations. The limitation of the motion is not essential in the following identification methods.

Figure 1 shows a space robot with an unknown object, and it also illustrates coordinate frames and symbols. The whole system is divided into three sub-body systems. The unknown object and

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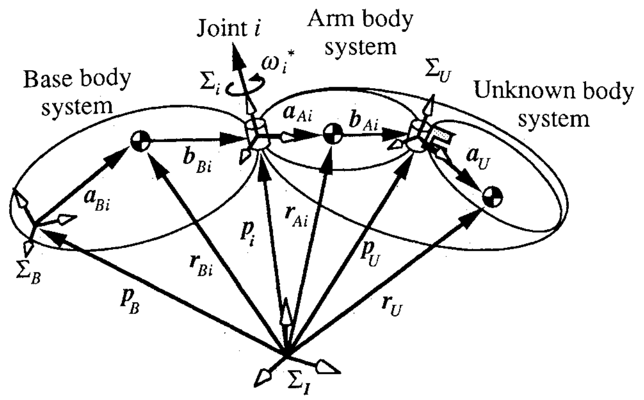

Fig. 1 Two rigid-body model of a free-flying space robot connected by a rotational joint.

end effector are named an unknown body system. The space robot without the unknown body system is divided into two sub-body systems. A body system including the satellite base body is called a base body system, and the other is called an arm body system. Vectors/tensors with suffixes added indicate where each vector or tensor is involved, i.e., quantities having suffix Bi are involved in the base body system, suffix Ai the arm body system, and suffix U the unknown body system.The coordinate frames—Σ_I, Σ_B, Σ_i, and Σ_U—are the inertial reference frame, the satellite base fixed frame, the arm body system fixed frame placed at driven joint i, and a work frame fixed on the manipulator hand and unknown object, respectively. The origin of Σ_I is placed at the mass center of the robot system.[1–6] Superscripts on the left shoulder of vectors/tensors denote in which coordinate frame the vectors/tensors are described, and vectors/tensors without superscripts are described with respect to Σ_I. Vectors $\boldsymbol{p}$ and $\boldsymbol{r}$ denote position vectors from the origin of Σ_I to those of the local coordinate frames and to the mass center of the sub-body systems, respectively; m is the mass of the sub-body systems, whereas $\boldsymbol{a}$ denotes the position vector from the origins of the sub-body fixed frame to the mass center of the sub-body system. The $\boldsymbol{I}$ is an inertia tensor around the mass center of the sub-body system; m, $\boldsymbol{a}$, and $\boldsymbol{I}$ are called the inertial parameters.

Measurements, Known Parameters, and Problem

Some measurements are supposed to be available for the identification, i.e., ${}^B\ddot{\boldsymbol{p}}_B$ and ${}^B\dot{\omega}_B$, by accelerometers mounted on the satellite base and angle θ_j and angular velocity $\dot{\theta}_j$ of joint j ($j=1,\dots,n$) by encoders and tachogenerators installed on joints. By integrating or differentiating those measurements with respect to time, the following values are obtained, i.e., ${}^B\dot{\boldsymbol{p}}_B$, ${}^B\omega_B$, and $\ddot{\theta}_i$. Because the tachogenerators are very noisy, one of the best practical methods to obtain $\ddot{\theta}_i$ is to calculate it from the joint angle measured by the encoder.[11] All of the links' parameters, i.e., the link parameters determining the relative position of links and the inertial parameters, except those of the unknown object, are assumed to be known. Then the inertial parameters of the base body system and arm body system are computed from the known parameters. Only the inertial parameters of the unknown body system, i.e., m_U, ${}^U\boldsymbol{a}_U$, and ${}^U\boldsymbol{I}_U$, are not known, and they are called the unknown inertial parameters. Under the aforementioned conditions, the parameter identification problem is defined as follows:

Problem: Estimate the inertial parameters of the unknown object grasped firmly by a manipulator hand from motions of the whole system.

For simplicity, the present problem is discussed in a two-body system, i.e., the base body system and a combined body system of the arm body system and unknown body system. The unknown inertial parameters are estimated from the motion when joint i is driven. If necessary, the driven joint would be changed and some other actions are used for the identification.

Kinematics

Kinematic formulations among the sub-body systems are described in their coordinate frames, which is suitable for Newton-Euler formulation of space robots.[5,6]

The velocity relations among the mass centers and the origins of the coordinate frames are described by the measurable quantities ${}^B\omega_B$, ${}^B\dot{\boldsymbol{p}}_B$, and $\dot{\theta}_i$, as follows:

$$ {}^B\dot{\boldsymbol{r}}_{Bi} = {}^B\dot{\boldsymbol{p}}_B + {}^B\omega_B \times {}^B\boldsymbol{a}_{Bi} \tag{1} $$

$$ {}^i\omega_i = {}^i\boldsymbol{R}_B\,{}^B\omega_B + {}^i\omega_i^* \tag{2} $$

$$ {}^i\dot{\boldsymbol{p}}_i = {}^i\boldsymbol{R}_B({}^B\dot{\boldsymbol{r}}_{Bi} + {}^B\omega_B \times {}^B\boldsymbol{b}_{Bi}) \tag{3} $$

$$ {}^i\dot{\boldsymbol{r}}_{Ai} = {}^i\dot{\boldsymbol{p}}_i + {}^i\omega_i \times {}^i\boldsymbol{a}_{Ai} \tag{4} $$

$$ {}^U\dot{\boldsymbol{p}}_U = {}^U\boldsymbol{R}_i({}^i\dot{\boldsymbol{r}}_{Ai} + {}^i\omega_i \times {}^i\boldsymbol{b}_{Ai}) \tag{5} $$

$$ {}^U\dot{\boldsymbol{r}}_U = {}^U\boldsymbol{R}_i({}^i\dot{\boldsymbol{p}}_U + {}^i\omega_i \times {}^i\boldsymbol{a}_U) \tag{6} $$

where ${}^i\omega_i^* = \dot{\theta}_i\,{}^i\boldsymbol{k}_i$, ${}^i\boldsymbol{k}_i$: unit in vector in rotational axis of joint i, and a time derivative of a vector $(\dot{\ })$ indicates the coordinate vector of a time derivative in the inertial reference frame. For example, ${}^i\dot{\boldsymbol{p}}_i$ is the time derivative in Σ_I of $\boldsymbol{p}_i$, which is expressed in Σ_i, i.e., ${}^i\dot{\boldsymbol{p}}_i = {}^i(\mathrm{d}\boldsymbol{p}_i/\mathrm{d}t) \neq \mathrm{d}\,{}^i\boldsymbol{p}_i/\mathrm{d}t$. A matrix $\boldsymbol{R}$ indicates the rotational transformation matrix, e.g., premultiplying by ${}^i\boldsymbol{R}_B$ transforms a vector expressed in the satellite base fixed frame Σ_B into a vector expressed in the arm body system fixed frame Σ_i.

The acceleration relations among the mass centers and the origins of the coordinate frames are described by the measurable quantities ${}^B\dot{\omega}_B$, ${}^B\ddot{\boldsymbol{p}}_B$, and ${}^i\dot{\omega}_i^*$ as follows:

$$ {}^B\ddot{\boldsymbol{r}}_{Bi} = {}^B\ddot{\boldsymbol{p}}_B + {}^B\dot{\omega}_B \times {}^B\boldsymbol{a}_{Bi} + {}^B\omega_B \times ({}^B\omega_B \times {}^B\boldsymbol{a}_{Bi}) \tag{7} $$

$$ {}^i\dot{\omega}_i = {}^i\boldsymbol{R}_B\,{}^B\dot{\omega}_B + {}^i\dot{\omega}_i^* \tag{8} $$

$$ {}^i\ddot{\boldsymbol{p}}_i = {}^i\boldsymbol{R}_B[{}^B\ddot{\boldsymbol{r}}_{Bi} + {}^B\dot{\omega}_B \times {}^B\boldsymbol{b}_{Bi} + {}^B\omega_B \times ({}^B\omega_B \times {}^B\boldsymbol{b}_{Bi})] \tag{9} $$

$$ {}^i\ddot{\boldsymbol{r}}_{Ai} = {}^i\ddot{\boldsymbol{p}}_i + {}^i\dot{\omega}_i \times {}^i\boldsymbol{a}_{Ai} + {}^i\omega_i \times ({}^i\omega_i \times {}^i\boldsymbol{a}_{Ai}) \tag{10} $$

$$ {}^U\ddot{\boldsymbol{p}}_U = {}^U\boldsymbol{R}_i[{}^i\ddot{\boldsymbol{r}}_{Ai} + {}^i\dot{\omega}_i \times {}^i\boldsymbol{b}_{Ai} + {}^i\omega_i \times ({}^i\omega_i \times {}^i\boldsymbol{b}_{Ai})] \tag{11} $$

$$ {}^U\ddot{\boldsymbol{r}}_U = {}^U\boldsymbol{R}_i[{}^i\ddot{\boldsymbol{p}}_U + {}^i\dot{\omega}_i \times {}^i\boldsymbol{a}_U + {}^i\omega_i \times ({}^i\omega_i \times {}^i\boldsymbol{a}_U)] \tag{12} $$

Identification Based on Momentum Conservation

An identification method based on linear and angular momentum conservation law is proposed in this section. Both linear and angular momentums of the whole system are supposed to be zero. This method is named the momentum conservation (MC) based method.

Linear momentum $\boldsymbol{P}$ of the whole system is given as

$$ \boldsymbol{P} = m_{Bi}\dot{\boldsymbol{r}}_{Bi} + m_{Ai}\dot{\boldsymbol{r}}_{Ai} + m_U\dot{\boldsymbol{r}}_U \tag{13} $$

The assumption $\boldsymbol{P} = 0$ yields the following equations:

$$ 0 = \frac{1}{m_U}(m_{Bi}\dot{\boldsymbol{r}}_{Bi} + m_{Ai}\dot{\boldsymbol{r}}_{Ai}) + \dot{\boldsymbol{r}}_U $$

$$ = \frac{1}{m_U}(m_{Bi}\dot{\boldsymbol{r}}_{Bi} + m_{Ai}\dot{\boldsymbol{r}}_{Ai}) + \dot{\boldsymbol{p}}_U + \omega_i \times \boldsymbol{a}_U \tag{14} $$

This is rewritten in Σ_U by using Eqs. (2–6), which are linearized with respect to the unknown inertial parameters as follows:

$$ -{}^U\dot{\boldsymbol{p}}_U = [{}^U\boldsymbol{P}_K, [{}^U\omega_i \times]] \begin{Bmatrix} \dfrac{1}{m_U} \\ {}^U\boldsymbol{a}_U \end{Bmatrix} \tag{15} $$

where

$$ {}^U\boldsymbol{P}_K \equiv {}^U\boldsymbol{R}_i(m_{Bi}{}^i\boldsymbol{R}_B{}^B\dot{\boldsymbol{r}}_{Bi} + m_{Ai}{}^i\dot{\boldsymbol{r}}_{Ai}) \tag{16} $$

where ${}^U\boldsymbol{P}_K$ denotes linear momentum of the system without the unknown body system. The cross product matrix $[\cdot\times]$ indicates the following matrix for a vector $\boldsymbol{v} = [v_1 \;\; v_2 \;\; v_3]^T$:

$$ [v\times] \equiv \begin{bmatrix} 0 & -v_3 & v_2 \\ v_3 & 0 & -v_1 \\ -v_2 & v_1 & 0 \end{bmatrix} \tag{17} $$

Angular momentum $\boldsymbol{L}$ of the whole system with respect to Σ_I is given as

$$ \boldsymbol{L} = \boldsymbol{I}_{Bi}\omega_B + \boldsymbol{I}_{Ai}\omega_i + \boldsymbol{I}_U\omega_i + \boldsymbol{r}_{Bi}\times m_{Bi}\dot{\boldsymbol{r}}_{Bi} $$
$$ + \boldsymbol{r}_{Ai}\times m_{Ai}\dot{\boldsymbol{r}}_{Ai} + \boldsymbol{r}_U\times m_U\dot{\boldsymbol{r}}_U \tag{18} $$

By substituting $\boldsymbol{L} = \boldsymbol{0}$ and Eq. (13) into Eq. (18) under $\boldsymbol{P} = \boldsymbol{0}$, the following equations are obtained:

$$ -\boldsymbol{I}_{Bi}\omega_B - m_{Bi}\dot{\boldsymbol{r}}_{Bi}\times(\boldsymbol{b}_{Bi} + \boldsymbol{a}_{Ai} + \boldsymbol{b}_{Ai}) - \boldsymbol{I}_{Ai}\omega_i $$
$$ - m_{Ai}\dot{\boldsymbol{r}}_{Ai}\times\boldsymbol{b}_{Ai} = (m_{Bi}\dot{\boldsymbol{r}}_{Bi} + m_{Ai}\dot{\boldsymbol{r}}_{Ai})\times\boldsymbol{a}_U + \boldsymbol{I}_U\omega_i \tag{19} $$

In the same manner as that of deriving Eq. (15), those equations are rewritten in Σ_U by using Eqs. (2–6) as

$$ {}^U\boldsymbol{L}_K = \{[{}^U\boldsymbol{P}_K\times][\#{}^U\omega_i]\}\begin{Bmatrix} {}^U\boldsymbol{a}_U \\ {}^U\boldsymbol{I}_U\# \end{Bmatrix} \tag{20} $$

where

$$ {}^U\boldsymbol{L}_K \equiv -{}^U\boldsymbol{R}_B{}^B\boldsymbol{I}_{Bi}{}^B\omega_B - {}^U\boldsymbol{R}_i{}^i\boldsymbol{I}_{Ai}{}^i\omega_i $$
$$ - m_{Bi}{}^U\dot{\boldsymbol{r}}_{Bi}\times({}^U\boldsymbol{b}_{bi} + {}^U\boldsymbol{a}_{Ai} + {}^U\boldsymbol{b}_{Ai}) - m_{Ai}{}^U\dot{\boldsymbol{r}}_{Ai}\times{}^U\boldsymbol{b}_{Ai} \tag{21} $$

and where $[\#\cdot]$ indicates the following matrix for a vector $\boldsymbol{v} = [v_1, v_2, v_3]^T$:

$$ [\#\boldsymbol{v}] = \begin{bmatrix} v_1 & v_2 & v_3 & 0 & 0 & 0 \\ 0 & v_1 & 0 & v_2 & v_3 & 0 \\ 0 & 0 & v_1 & 0 & v_2 & v_3 \end{bmatrix} \tag{22} $$

The vector $\{\cdot\#\}$ indicates a vector

$$ \{\boldsymbol{I}\#\} \equiv (I_{11}, I_{12}, I_{13}, I_{22}, I_{23}, I_{33})^T \tag{23} $$

for a symmetric matrix

$$ \boldsymbol{I} = \begin{bmatrix} I_{11} & I_{12} & I_{13} \\ I_{12} & I_{22} & I_{23} \\ I_{13} & I_{23} & I_{33} \end{bmatrix} $$

Combining Eqs. (15) and (20) yields

$$ \begin{Bmatrix} -{}^U\dot{\boldsymbol{p}}_U \\ {}^U\boldsymbol{L}_K \end{Bmatrix} = \begin{Bmatrix} {}^U\boldsymbol{P}_K & [{}^U\omega_i\times] & \boldsymbol{0} \\ \boldsymbol{0} & [{}^U\boldsymbol{P}_K\times] & [\#{}^U\omega_i] \end{Bmatrix} \begin{Bmatrix} \dfrac{1}{m_U} \\ {}^U\boldsymbol{a}_U \\ {}^U\boldsymbol{I}_U\# \end{Bmatrix} \tag{24} $$

Finally, the equations of linear and angular momentum conservation are linearized with respect to the unknown parameters m_U, ${}^U\boldsymbol{a}_U$, and ${}^U I_U$. The left-hand side and all elements of the first matrix on the right-hand side can be calculated from measurements, i.e., ${}^B\dot{\boldsymbol{p}}_B$, ${}^B\omega_B$, and $\dot{\theta}_i$, and all of the joint angles θ_j ($j = 1, \ldots, n$). This is the fundamental equation of the MC-based method for the deterministic parameter identification.

A single set of the measurements cannot determine all of the unknown inertial parameters because Eq. (24) is indeterminate, i.e., the first matrix of the right-hand side has six rows and ten columns. Other sets of equations are obtained from other sets of measurements corresponding to different joint angles θ_i. A complete set of the simultaneous equations is obtained by combining some equations. By solving the simultaneous equations, one can determine all of the unknown inertial parameters. If the simultaneous equations are still indeterminate, other joints are driven one after another to yield a complete set of simultaneous equations. By solving the combined simultaneous equations, one can determine all of the unknown inertial parameters. If the obtained simultaneous equations are overdetermined, e.g., the measurements have some observation noise, the left pseudoinverse is used in the sense of the least-square error.

Identification Based on Equations of Motion

In this section, an identification method based on equations of motion in the Newton-Euler formulation is proposed, which is different from that in the preceding section. No external forces and torques are assumed. This method is named the equations of motion (EM) based method.

As illustrated in Fig. 2, $\boldsymbol{f}$ and $\boldsymbol{n}$ denote translational forces and torques applied to the origin of the local coordinate frames. And $\hat{\boldsymbol{f}}$ and $\hat{\boldsymbol{n}}$ denote equivalent translational forces and torques with respect to the mass center of the sub-body system, which are computed from $\boldsymbol{f}$ and $\boldsymbol{n}$. Equilibriums of translational forces among the sub-body systems are given as

$$ \boldsymbol{0} = {}^B\boldsymbol{R}_i{}^i\boldsymbol{f}_i + {}^B\hat{\boldsymbol{f}}_{Bi} \tag{25} $$

$$ {}^i\boldsymbol{f}_i = {}^i\boldsymbol{R}_U{}^U\boldsymbol{f}_U + {}^i\hat{\boldsymbol{f}}_{Ai} \tag{26} $$

$$ {}^U\boldsymbol{f}_U = {}^U\hat{\boldsymbol{f}}_U \tag{27} $$

The equivalent translational forces with respect to their mass centers are given from Newton's equations of motion as follows:

$$ {}^B\hat{\boldsymbol{f}}_{Bi} = m_{Bi}{}^B\ddot{\boldsymbol{r}}_{Bi} \tag{28} $$

$$ {}^i\hat{\boldsymbol{f}}_{Ai} = m_{Ai}{}^i\ddot{\boldsymbol{r}}_{Ai} \tag{29} $$

$$ {}^U\hat{\boldsymbol{f}}_U = m_U{}^U\ddot{\boldsymbol{r}}_U \tag{30} $$

Rearranging the equilibrium of translational forces by using Eqs. (28–30) yields

$$ m_U{}^U\ddot{\boldsymbol{r}}_U = -m_{Bi}{}^U\ddot{\boldsymbol{r}}_{Bi} - m_{Ai}{}^U\ddot{\boldsymbol{r}}_{Ai} \tag{31} $$

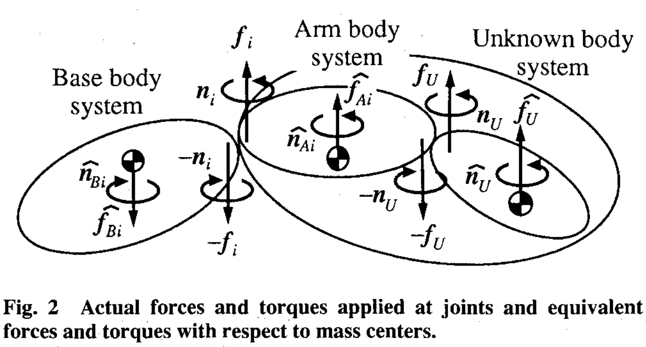

Fig. 2 Actual forces and torques applied at joints and equivalent forces and torques with respect to mass centers.

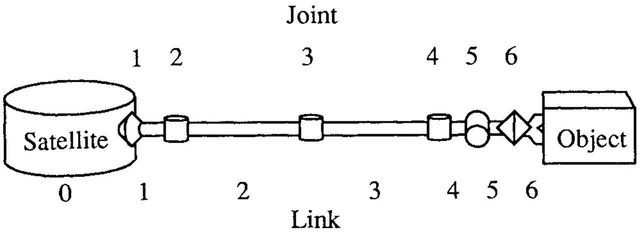

Fig. 3 Free-flying space robot model with a six-DOF manipulator and an unknown object.

By substituting Eqs. (7), (10), and (12) into Eqs. (31), the following equations are obtained:

$$-m_U{}^U\ddot{\boldsymbol{p}}_U = m_U[{}^U\dot{\omega}_i \times {}^U\boldsymbol{a}_U + {}^U\omega_i \times ({}^U\omega_i \times {}^U\boldsymbol{a}_U)] + m_{Bi}{}^U\ddot{\boldsymbol{r}}_{Bi} + m_{Ai}{}^U\ddot{\boldsymbol{r}}_{Ai} \tag{32}$$

The present equations are linearized with respect to the unknown inertial parameters as

$$-{}^U\ddot{\boldsymbol{p}}_U = \begin{bmatrix} {}^U\boldsymbol{f}_K & [{}^U\dot{\Omega}_i\times] \end{bmatrix} \begin{Bmatrix} \dfrac{1}{m_U} \\ {}^U\boldsymbol{a}_U \end{Bmatrix} \tag{33}$$

where

$${}^U\boldsymbol{f}_K \equiv {}^U\boldsymbol{R}_i(m_{Bi}{}^i\boldsymbol{R}_B{}^B\ddot{\boldsymbol{r}}_{Bi} + m_{Ai}{}^i\ddot{\boldsymbol{r}}_{Ai}) \tag{34}$$

$$[{}^U\dot{\Omega}_i\times] \equiv [{}^U\dot{\omega}_i\times] + [{}^U\omega\times]^2 \tag{35}$$

Equilibriums of rotational forces among the sub-body systems are derived from the equations of motion in the Newton-Euler formulation as

$$\boldsymbol{0} = {}^B\boldsymbol{R}_i{}^i\boldsymbol{n}_i + {}^B\hat{\boldsymbol{n}}_{Bi} + {}^B\boldsymbol{b}_{Bi} \times ({}^B\boldsymbol{R}_i{}^i\boldsymbol{f}_i) \tag{36}$$

$${}^i\boldsymbol{n}_i = {}^i\boldsymbol{R}_U{}^U\boldsymbol{n}_U + {}^i\hat{\boldsymbol{n}}_{Ai} + {}^i\boldsymbol{a}_{Ai} \times {}^i\boldsymbol{f}_i + {}^i\boldsymbol{b}_{Ai} \times {}^i\boldsymbol{R}_U{}^U\boldsymbol{f}_U \tag{37}$$

$${}^U\boldsymbol{n}_U = {}^U\hat{\boldsymbol{n}}_U + {}^U\boldsymbol{a}_U \times {}^U\boldsymbol{f}_U \tag{38}$$

The equivalent torques around their mass centers are given from Euler's equations of motion as follows:

$${}^B\hat{\boldsymbol{n}}_{Bi} = {}^B\boldsymbol{I}_{Bi}{}^B\dot{\omega}_B + {}^B\omega_B \times ({}^B\boldsymbol{I}_{Bi}{}^B\omega_B) \tag{39}$$

$${}^i\hat{\boldsymbol{n}}_{Ai} = {}^i\boldsymbol{I}_{Ai}{}^i\dot{\omega}_i + {}^i\omega_i \times ({}^i\boldsymbol{I}_{Ai}{}^i\omega_i) \tag{40}$$

$${}^U\hat{\boldsymbol{n}}_U = {}^U\boldsymbol{I}_U{}^U\dot{\omega}_i + {}^U\omega_i \times ({}^U\boldsymbol{I}_U{}^U\omega_i) \tag{41}$$

Rearranging Eq. (41) by using the previous equation yields

$${}^U\boldsymbol{n}_U = (m_{Bi}{}^U\ddot{\boldsymbol{r}}_{Bi} + m_{Ai}{}^U\ddot{\boldsymbol{r}}_{Ai}) \times {}^U\boldsymbol{a}_U + {}^U\boldsymbol{I}_U{}^U\dot{\omega}_i + {}^U\omega_i \times ({}^U\boldsymbol{I}_U{}^U\omega_i) \tag{42}$$

The present equations are linearized with respect to the unknown inertial parameters as

$${}^U\boldsymbol{n}_U = \left\{ [{}^U\boldsymbol{f}_K\times] \;\; [\#{}^U\dot{\Omega}_i] \right\} \begin{Bmatrix} {}^U\boldsymbol{a}_U \\ {}^U\boldsymbol{I}_U\# \end{Bmatrix} \tag{43}$$

where

$$[\#{}^U\dot{\Omega}_i] \equiv [\#{}^U\dot{\omega}_i] + [{}^U\omega_i\times][\#{}^U\omega_i] \tag{44}$$

And ${}^U\boldsymbol{n}_U$ in Eq. (43) is given by the following equation:

$${}^U\boldsymbol{n}_U = {}^U\boldsymbol{R}_B[({}^B\boldsymbol{b}_{Bi} + {}^B\boldsymbol{a}_{Ai} + {}^B\boldsymbol{b}_{Ai}) \times {}^B\hat{\boldsymbol{f}}_{Bi} - {}^B\hat{\boldsymbol{n}}_{Bi}] + {}^U\boldsymbol{R}_i({}^i\boldsymbol{b}_{Ai} \times {}^i\hat{\boldsymbol{f}}_{Ai} - {}^i\hat{\boldsymbol{n}}_{Ai}) \tag{45}$$

where ${}^B\hat{\boldsymbol{f}}_{Bi}$, ${}^B\hat{\boldsymbol{n}}_{Bi}$, ${}^i\hat{\boldsymbol{f}}_{Ai}$, and ${}^i\hat{\boldsymbol{n}}_{Ai}$ are computed from Eqs. (29), (39), (28), and (40), respectively.

By combining Eq. (33) with Eq. (43), the following equations are obtained:

$$\begin{Bmatrix} -{}^U\ddot{\boldsymbol{p}}_U \\ {}^U\boldsymbol{n}_U \end{Bmatrix} = \begin{bmatrix} {}^U\boldsymbol{f}_K & [{}^U\dot{\Omega}_i\times] & \boldsymbol{0} \\ \boldsymbol{0} & [{}^U\boldsymbol{f}_K\times] & [\#{}^U\dot{\Omega}_i] \end{bmatrix} \begin{Bmatrix} \dfrac{1}{m_U} \\ {}^U\boldsymbol{a}_U \\ {}^U\boldsymbol{I}_U\# \end{Bmatrix} \tag{46}$$

The left-hand side and all elements of the first matrix on the right-hand side can be calculated from measurements, i.e., ${}^B\ddot{\boldsymbol{p}}_B$, ${}^B\dot{\omega}_B$, ${}^B\dot{\boldsymbol{p}}_B$, ${}^B\omega_B$, $\ddot{\theta}_i$, $\dot{\theta}_i$, and all of the joint angles θ_j ($j = 1, \dots, n$). This is the fundamental equation of the EM-based method for the deterministic parameter identification. Although Eq. (46) is also indeterminate like Eq. (24), the unknown inertial parameters are determined by using some sets of measurements in the same manner as in the method in the preceding section.

Kawasaki[8] proposed an identification method for inertial parameters of an object handled by a conventional manipulator, which has the inertial fixed base on the ground. Kawasaki's method estimates the parameters by using the equality of the inertial forces of the unknown object and the applied forces computed from the joint torques to be generated. In the same manner, one can derive a fundamental equation for the free-flying space robot using the equilibrium of the inertial forces of the unknown object and the applied forces. But in this case one must estimate parameters of the joint frictional resistant torque simultaneously or use the torque sensor on each articular joint to measure the generated torque.[8] However, one can compute the forces applied to the unknown object from the motion of the base body system since the free-flying space robot is floating and free to translate and rotate. An advantage of the EM-based method is that one does not have to consider the frictional resistant torque and noises of joint torque sensors because only the measurements of motions, i.e., linear/angular velocities and accelerations, are used with no information of the forces and torques utilized.

Numerical Simulations

Identification with No Sensor Noise

The proposed two identification methods are examined for a free-flying space robot with a six-degree-of-freedom (DOF) manipulator that can grasp an unknown object firmly as illustrated in Fig. 3. The satellite base is named link 0. Links of the manipulator are numbered in sequential order, and the manipulator hand is link 6. Joints are also numbered in serial order, and the joint between link 0 and link 1 is named joint 1. The third axis of the

Table 1 Specifications of space robot model with six-DOF manipulator

	Mass, kg	Length, m		Inertia tensor, kg · m²		
Link i	m_i	${}^i\boldsymbol{a}_i(1)$	${}^i\boldsymbol{b}_i(1)$	${}^i\boldsymbol{I}_i(1,1)$	${}^i\boldsymbol{I}_i(2,2)$	${}^i\boldsymbol{I}_i(3,3)$
0	2000.0	0.00	1.50	1500.00	1500.00	2250.00
1	5.0	0.13	0.13	0.03	0.03	0.01
2	50.0	1.25	1.25	0.06	26.07	26.07
3	50.0	1.25	1.25	0.06	26.07	26.07
4	10.0	0.25	0.25	0.01	0.21	0.21
5	5.0	0.13	0.13	0.01	0.03	0.03
6	5.0	0.13	0.13	0.03	0.03	0.01
6 with object	105.0	0.72	——	10.22	13.22	13.67

link i fixed coordinate frame corresponds to the joint i axis, and the first axis points to the origin of the joint $i + 1$ fixed coordinate frame if possible. The origin of the link i fixed coordinate frame is located at its mass center. Parameters of this model are listed in Table 1. All of the inertial tensors ${}^i\boldsymbol{I}_i$ of links i ($i = 0, 1, \ldots, 6$) are denoted as diagonal matrices. Position vectors ${}^i\boldsymbol{a}_i$ and ${}^i\boldsymbol{b}_i$ have zeros in the second and the third elements. The ith element of vector $\boldsymbol{a}$ and the jth row and the kth column element of matrix $\boldsymbol{I}$ are represented as $\boldsymbol{a}(i)$ and $\boldsymbol{I}(j, k)$, respectively. The inertia parameters of the unknown body system, i.e., the unknown body with link 6, are estimated assuming that the parameters of all of the other links are known.

Each test motion starts from the same initial state of the space robot, i.e., the configuration of the manipulator is to be straight, as shown in Fig. 3. In the identification process, a joint is driven at a time and the other joints are fixed in the initial state. One drives the joints from joint 1 to joint 6 one after another and obtains one set of measurements of each motion. One identifies the parameters, using the obtained measurements of the motion and the previously obtained measurements. For example, two sets of measurements obtained from joint 1 and joint 2 motions and six sets of measurements from joint 1 to joint 6 motions are used for the identification of joint 2 driven and that of joint 6 driven, respectively. The determination processes of the unknown inertial parameters by using the MC-based method are presented in Table 2. In the table, only five nonzero terms of the unknown inertial parameters are listed. The off-diagonal terms of the inertial tensor ${}^U\boldsymbol{I}_U$, ${}^U\boldsymbol{a}_U$ (2), and ${}^U\boldsymbol{a}_U$ (3) are to be zero when the nonzero terms of the unknown inertial parameters are estimated exactly. The example shows that the inertial parameters of the object can be identified by using the MC-based method proposed in this study. A similar result is obtained when the EM-based method is used. After the fifth trial of the joint motion, all of the inertial parameters of the object are determined by the two methods.

The preceding results indicate that the six-DOF manipulator is not needed to estimate all of the unknown inertial parameters. As a result, the handled object is moved around three orthogonal rotational axes and transverse directions after joint 5 motion. Hence, a set of three motions is examined in the identification, where only joints 2 and 5 are driven. The two joints are driven one by one around the initial posture of the manipulator. Then joint 5 is turned 90 deg, and joint 2 is driven. After the three joint motions, all of the unknown inertial parameters are determined exactly, although simulation results are not shown here. The suitable change of the manipulator configuration can reduce the number of the joint test motion. However, the following important problems[12] are open to be solved: 1) what is the suitable and minimum sequence of the test motions? and 2) how is the test sequence constructed so as to be sufficiently rich to determine the unknown parameters?

Table 2 Identified results based on momentum conservation

Driven	Mass, kg	Mass center, m	Inertia tensor, kg·m^2		
joint	m_U	${}^U\boldsymbol{a}_U(1)$	${}^U\boldsymbol{I}_U(1,1)$	${}^U\boldsymbol{I}_U(2,2)$	${}^U\boldsymbol{I}_U(3,3)$
1	∞	0.0	0.0	0.0	0.0
2	1.9×10^{-4}	2.4×10^{6}	-7.5×10^{8}	-1.9×10^{9}	2.4×10^{-2}
3	-8.9×10^{-2}	-2.1×10^{4}	2.6×10^{7}	1.5×10^{6}	-1.2×10^{-2}
4	-5.6×10^{-2}	-1.0×10^{4}	1.4×10^{7}	1.8×10^{5}	2.11
5	105.0	0.72	10.22	13.22	13.67
6	105.0	0.72	10.22	13.22	13.67

Table 3 Identified results considering measurement noise

ID	Mass, kg	Mass center, m	Inertia tensor, kg·m^2		
method	m_U	${}^U\boldsymbol{a}_U(1)$	${}^U\boldsymbol{I}_U(1,1)$	${}^U\boldsymbol{I}_U(2,2)$	${}^U\boldsymbol{I}_U(3,3)$
MC[a]	103.4	0.72	11.02	11.29	14.31
Error, %	−1.5	0.3	7.8	−14.6	0.3
EM[b]	116.6	0.61	11.38	20.64	13.93
Error, %	−11.1	−15.7	11.3	56.1	1.9

[a]MC: momentum conservation. [b]EM: equations of motion.

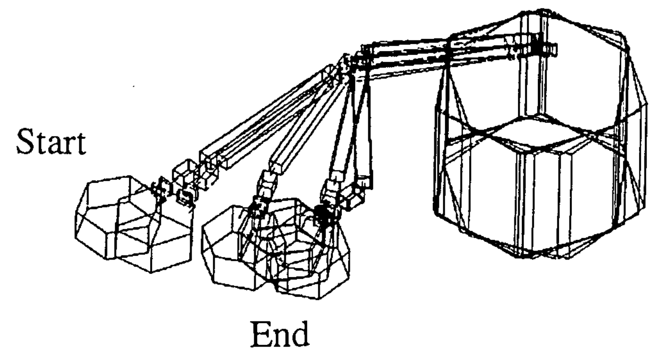

Fig. 4 Movement of space robot handling an unknown object.

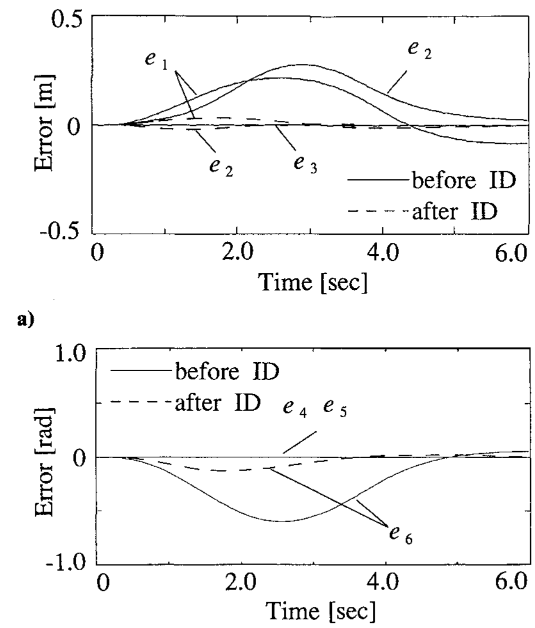

Fig. 5 Error at end effector: a) position error and b) orientation error.

Influence of Sensor Noise

Estimation errors of the inertial parameters caused by the sensor noise are discussed through a numerical simulation, using the preceding six-DOF model. The measured quantities during the actions are ${}^B\ddot{\boldsymbol{p}}_B$, ${}^B\dot{\boldsymbol{p}}_B$, ${}^B\dot{\omega}_B$, ${}^B\omega_B$, $\ddot{\theta}_i$, $\dot{\theta}_i$, and θ_i. The sensor noises added to the measurements are modeled as a normally distributed random number that has zero mean. The standard deviations of the sensor noises used in the following simulation are listed as 0.031 m/s^2 in ${}^B\ddot{\boldsymbol{p}}_B$, 0.031 m/s in ${}^B\dot{\boldsymbol{p}}_B$, 0.1 rad/s^2 in ${}^B\dot{\omega}_B$ and $\ddot{\theta}_i$, 0.1 rad/s in ${}^B\omega_B$ and $\dot{\theta}_i$, and 0.1 rad in θ_i. The standard deviations reach about 10% of the measured maximum quantities. It is difficult to estimate the unknown inertial parameters directly from the measurements with noises. And the time history of the measurements are least-squared error curve fitted by a polynomial expression. Five sets of measurements are selected from the curve-fitted time histories for each action. In total, 30 sets of measurements are used to estimate the unknown inertial parameters in Eq. (24) or Eq. (46), and the results are shown in Table 3.

The MC-based method yields better estimation than the EM-based method because the MC-based method is affected only by the noises on the rate measurements, whereas the EM-based method is affected by the noises on the acceleration measurements as well as those on the rate measurements.

Influence on Control

The influence of the identified results on a control is illustrated through numerical simulations using the preceding six-DOF

Table 4 Specifications of hardware robot model and experimentally identified results

	Mass m_i, kg	Mass center ${}^i\boldsymbol{a}_i(1)$, m	Inertia moment ${}^i\boldsymbol{I}_i(3,3)$, kg·m^3
Link 0	8.30	0.247	0.139
Link 1	1.47	0.252	0.030
Link 2 with object	3.61	0.194	0.085
Identified results			
Link 2 with object	3.77	0.170	0.088
Error, %	−4.4	−12.0	3.5

model. The resolved acceleration control (RAC) for space robots[5,6] is used to move the manipulator hand along a desired path.

Figure 4 shows the movements of the space robot with a handled object controlled by the RAC controller that does not consider the inertial parameters of the object. Movement of the robot viewed from the inertial frame in every 1 s is illustrated. Specifications of the robot are listed in Table 1. The desired path of the manipulator hand goes straight from the initial position/orientation to 2 m toward the satellite base and 1 m left with the same orientation. The path is given by a sinusoidal curve with respect to time, and its rate and acceleration are continuous and differentiable. The desired path goes to the endpoint from the start point for the first 4 s, whereas the control is continued for 6 s. Figure 5 shows the position error $[e_1, e_2, e_3]^T$ in Σ_I and orientation error $[e_4, e_5, e_6]^T$ of roll-pitch-yaw angle between the end effector and the desired path. Both errors are relatively large during the path tracking control.

The generalized Jacobian matrix contains the inertial parameters as well as the link parameters, i.e., geometric parameters. Hence the generalized Jacobian matrix and the inertial matrix vary when the manipulator hand grasps an object because the inertial parameters of the tip link change. The large errors result because the handled object has not been modeled in the controller. The handled object of only 5% mass of the satellite base yields such large errors during the path tracking control in this example.

Next, the space robot is controlled by the RAC, which uses the inertial parameter identified by the MC-based method in the preceding section. The simulation result is also illustrated in Fig. 5. The hand tracks the desired path more closely than the motion before the identification. If the inertial parameters of the object are estimated accurately, the RAC moves the manipulator hand along the desired path without error. The tracking errors are due to the parameter estimation error caused by the sensor noises. As a result of the present examples, significance of the parameter identification is demonstrated to control the space manipulator with an unknown object. Since the generalized Jacobian matrices play a very important role in control of the space robots, the inertial parameter identification is necessary to both the RAC and other control methods.

Hardware Experiment

The proposed identification method is verified by means of a hardware system[13] simulating a free-flying space robot, which was constructed by referring to the experimental systems.[14–16] The experimental system is schematically illustrated in Fig. 6. The robot model consists of a satellite base and a manipulator with two links. The space robot model is supported on the horizontal table by air pads, which realizes free motions in rotational and translational directions on the plane table.

The position and attitude of the satellite base are measured by the Video Tracker system, i.e., the optical position sensor system, with a 60-Hz sampling rate, and its standard deviation of measurement error is 1.6 mm after appropriate calibration. Each articular joint is driven by a dc servomotor and has a brake to fix the joint. The joint angles can be measured by using optical rotary encoders whose resolution is 1.57×10^{-4} rad.

The links and joints are numbered from the satellite base to the tip of the manipulator in the same manner as in the numerical simulations. The satellite base has a square form with about 0.3 m on each side, and both links 1 and 2 are 0.3 m in length. The specifi-

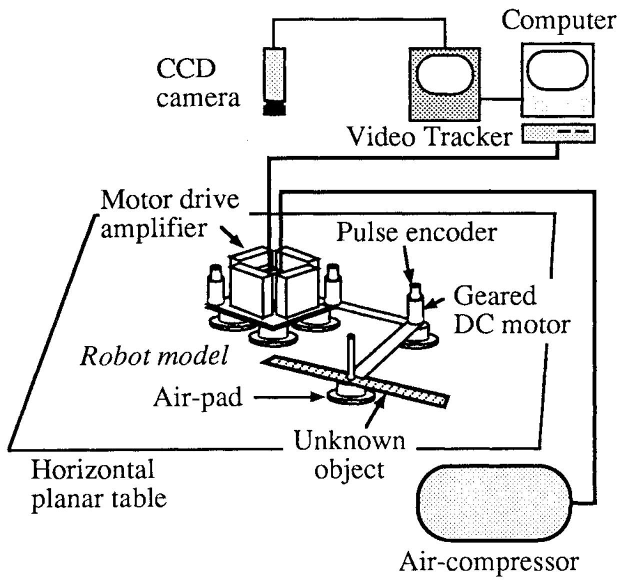

Fig. 6 Schematic diagram of hardware setup.

cations of the robot model are listed in Table 4. Each link of the robot model is symmetric with its first axis, and all ${}^i\boldsymbol{a}_i(2)$ are zeros. The mass ratio of the rotational axis side to the whole actuator is not given, and the ratio of 0.3 is assumed. The unknown object is fixed at the tip of link 2. The inertial parameters of the unknown body system, i.e., link 2 with the unknown object, are estimated.

One joint of the manipulator is fixed by the brake and the other joint is driven. Then the position and orientation measurements of the satellite base and the angular measurements of the joints are recorded. The robot model is stationary at the initial time. Several sets of the movements were recorded for several combinations of the driven joint and postures of the manipulator. The recorded time histories of measurements are polynomially approximated by the least-squared-error method in the same manner as the numerical simulations. Also, the approximated curves are differentiated with respect to time. Five sets of the measurements of the processed data are selected for each action, and several records of actions are used to estimate the unknown inertial parameters.

The number of the inertial parameters of the handled object is 10 when the space robot moves in the three-dimensional space, whereas the number reduces to 4 when the motion of the robot is constrained in the two-dimensional plane. The reduced inertial parameters are the mass m_U, the mass center ${}^U\boldsymbol{a}_U(1)$ and ${}^U\boldsymbol{a}_U(2)$, and the moment of inertia ${}^U\boldsymbol{I}_U(3,3)$. The fundamental equations for the two-dimensional case are immediately obtained by eliminating the needless terms in Eqs. (24) and (46).

To get the acceleration information of the measurements for the EM-based method, the approximated curves have to be differentiated twice with respect to time. Hence the identified results by the EM-based method are not satisfactory. The identification results by the MC-based method are given in Table 4. A relatively good result is obtained, although the measurements of the Video Tracker system containing rather large errors are used to calculate the orientation of the satellite base and the linear and angular rates.

Conclusions

Two identification methods have been proposed to estimate the inertial parameters, i.e., mass, mass center, and inertial tensor, of an object handled by free-flying space robots, under the conditions that no external forces and torques are applied to the space robot. Both of them have yielded fundamental equations for the identification that are linearized with respect to the unknown inertial parameters. One is based on the conservation principle of linear and angular momentum, and the other is based on Newton-Euler equations of motion. The feature of the proposed method is to use the kinematical information. The kinematical information is measured by sensors installed on the satellite base or on the other part of the system. Therefore, the space robot can identify the unknown object with no information from an external system, and the identified result is reflected on the control performance.

All of the inertial parameters of the handled object have been exactly estimated by the proposed method in the numerical simulations. When the measurements contain some sensor noises, the parameters have been estimated with rather small error by using the polynomial approximation of measurements by means of the least-squared-error method. The significance of the inertial parameter identification has been demonstrated through a control simulation of a space robot handling an unknown object. Finally, the proposed identification methods have been successfully verified through a hardware experiment.

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