Acta Astronautica 132 (2017) 131–142

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

On-orbit identifying the inertia parameters of space robotic systems using simple equivalent dynamics

Wenfu Xu[a,*], Zhonghua Hu[a], Yu Zhang[a], Bin Liang[a,b]

[a] *Shenzhen Graduate School, Harbin Institute of Technology, PR China*
[b] *Department of Automation, Tsinghua University, PR China*

ARTICLE INFO

Keywords:
Space robot
Space manipulator
Inertia parameters identification
On-orbit servicing
Simple equivalent dynamics

ABSTRACT

After being launched into space to perform some tasks, the inertia parameters of a space robotic system may change due to fuel consumption, hardware reconfiguration, target capturing, and so on. For precision control and simulation, it is required to identify these parameters on orbit. This paper proposes an effective method for identifying the complete inertia parameters (including the mass, inertia tensor and center of mass position) of a space robotic system. The key to the method is to identify two types of simple dynamics systems: equivalent single-body and two-body systems. For the former, all of the joints are locked into a designed configuration and the thrusters are used for orbital maneuvering. The object function for optimization is defined in terms of acceleration and velocity of the equivalent single body. For the latter, only one joint is unlocked and driven to move along a planned (exiting) trajectory in free-floating mode. The object function is defined based on the linear and angular momentum equations. Then, the parameter identification problems are transformed into non-linear optimization problems. The Particle Swarm Optimization (PSO) algorithm is applied to determine the optimal parameters, i.e. the complete dynamic parameters of the two equivalent systems. By sequentially unlocking the 1st to nth joints (or unlocking the nth to 1st joints), the mass properties of body 0 to n (or n to 0) are completely identified. For the proposed method, only simple dynamics equations are needed for identification. The excitation motion (orbit maneuvering and joint motion) is also easily realized. Moreover, the method does not require prior knowledge of the mass properties of any body. It is general and practical for identifying a space robotic system on-orbit.

1. Introduction

Space robots will play important roles in future space activities such as inspecting, repairing, upgrading and refueling spacecraft [1–5]. They have the potential to extend satellite life, enhance space system capability, decrease operation costs and clean up space debris. Due to dynamic coupling, the motion of a manipulator alters the position and attitude of the base. End-effectors lose the desired target pose (position and attitude) due to the motion of the base [6,7]. This complicates the trajectory planning and control of a space robotic system. Scholars have presented some effective methods for handling the dynamic coupling problem. Umetani and Yoshida presented the generalized Jacobian matrix and resolved the motion control method [8]. Nakamura and Mukherjee [9] used the “bidirectional approach” to plan a path for controlling both the manipulator configuration and spacecraft orientation. Nenchev et al. [10] proposed the reaction null-space control method to address dynamic interaction problems and suppress vibration in the flexible base manipulator. Yoshida et al. [11] addressed the zero reaction maneuver concept and demonstrated it on the ETS-VII. Xu et al. [12] proposed a method based on the particle swarm optimization algorithm to plan the Cartesian point-to-point path of the end-effector and adjust the base attitude simultaneously. Oda et al. [13] proposed a coordinated control method of a space robotic system, simultaneously using the arm controller and the satellite attitude controller. The former estimates the disturbance momentum according to the planned motion of the arm and the current attitude of the base. Then, it sends the results to the satellite controller, which uses the estimated values as feedforward commands to compensate for the reaction of the arm. Angel Flores-Abad et al. [14] proposed an optimal control method of space robots for capturing a tumbling object with uncertainties. Zhu et al. [15,16] proposed a visual servo control framework and corresponding close-loop position-based control strategy for non-cooperative target autonomous capture. The pose and motion of the target is estimated by the extended Kalman filter (EKF). The preceding methods require accurate knowledge of the inertia parameters (mass, inertia tensor, position of center of mass) of each

* Corresponding author.
E-mail addresses: wfxu@hit.edu.cn (W. Xu), hitsz_hzh@163.com (Z. Hu), zy_hitsz@163.com (Y. Zhang), bliang@mail.tsinghua.edu.cn (B. Liang).

http://dx.doi.org/10.1016/j.actaastro.2016.12.031
Received 28 March 2016; Accepted 22 December 2016
Available online 25 December 2016
0094-5765/

body. Except for control purpose, these parameters are very important for simulation and analysis on the ground to verify and evaluate the system design, mission planning, tele-operation, and other key issues of space robots. However, these parameters of the system may change on orbit for many reasons, such as fuel consumption, payload deployment, hardware reconfiguration, target capturing, spacecraft docking and mechanical malfunction. Methods are therefore required to identify these dynamic parameters.

For a space robot, whose base is free-floating in 3D space, it has six more degrees of freedoms – three for translation and three for rotation. The dynamic modeling and parameter identification are more challenging. Murotsu [17] proposed two methods for estimating the unknown inertial parameters of manipulated objects. One is based on the linear and angular momentum conservation law. The first method involves measuring the displacements and velocities of the satellite and joints. The second method is based on Newton-Euler equations of motion. Identification methods based on these equations of motion usually use force and torque measurements and identify the target parameters. Yoshida et al. [18] presented a method for identifying the inertia parameters of a free-flying space robot. Using the conservation of momentum laws and considering the effect of gravity gradient torque (unique characteristics in space), the identification algorithm did not require torque or acceleration measurement. However, the mass and centroid position of each body were assumed to be known and not needed to be identified. Lampariello [19] proposed a method for identifying the inertial parameters of a free-flying robot directly on orbit using accelerometers. The method was applied to identify the base body and load on the end-effector, emphasizing the experimental design. In this case, the manipulator parameters were assumed to be known in advance. Abiko and Hirzinger [20] studied online parameter adaptation for momentum control in the post-grasping of a tumbling target with model uncertainty. The proposed adaptation algorithm required measuring the values of the coupling force between the base satellite and robot arm. Only the target's inertia parameters were identified. Ma and Dang [21] presented a robotics-based method for the on-orbit identification of the inertia properties of spacecraft (the base of the space robot), which required accurate kinematics and the dynamic parameters of the manipulator to be known. Thai et al. [22] developed an online momentum-based inertia-parameter identification method for a grasped tumbling target in which the mass properties of the base and manipulator were assumed to be known.

This paper presents a practical and effective approach to identifying the complete inertia parameters of each body of the whole space robotic system, including the base satellite, space manipulator and grasped target. These parameters include the mass, inertia tensor and center of mass position. Only simple dynamics equations are used for inertia parameters identification. The excitation motion is also easily realized. Moreover, no prior knowledge of the mass properties of any system body is required. It is general and practical for on-orbit identifying a space robotic system.

The remainder of this paper is organized as follows. In Section 2, we derive the kinematics and momentum equations of a free-floating space robotic system, establishing the theoretical foundation for inertia parameters identification. In Section 3, we propose an identification method for complete inertial parameters of all bodies based on simple equivalent dynamic models. The identification problem is transformed into non-linear optimization problems. The object functions about the parameters to be determined are correspondingly defined. Section 4 resolves the inertia parameters using the Particle Swarm Optimization (PSO) algorithm. The proposed method is verified in Section 5 based on the simulations of a practical example. The final section presents the summary and conclusion.

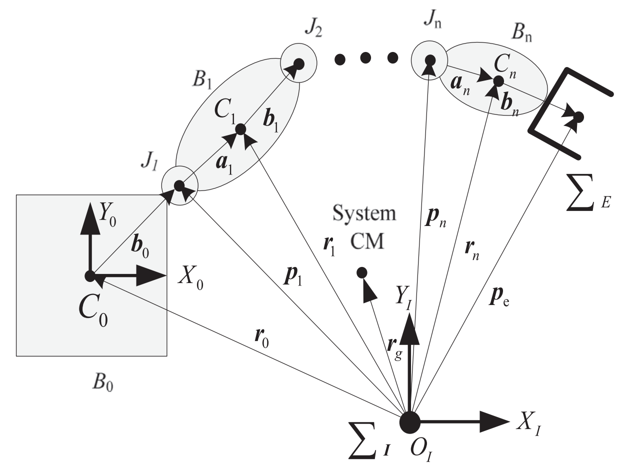

Fig. 1. General model of a serial space robot.

2. Modeling of space robotic system

2.1. Kinematics equations

It is assumed that a space robot is composed of a carrier spacecraft (known as the *Space Base or Base*) and an n-DOFs (degrees of freedom) manipulator (known as the *Space Manipulator*). The space robot captures and services a target satellite (known as the *Target*). The space robotic system can be considered as a serial system composed of n+1 links which are connected by n active joints. The kinematic link of the space robotic system is shown on Fig. 1. Each joint is assumed to have only one DOF. B_0 denotes the satellite main body. B_i (i=1, ..., n) denotes the ith link of the manipulator. J_i is the joint connecting B_{i-1} and B_i. C_i is the position of the center of mass (CM) of B_i.

Some symbols and variables are defined as follows:

$\sum_I$: the inertia frame, also denoted as $\{x_I, y_I, z_I\}$.

$\sum_i$(i=0, ..., n): the body fixed frame of B_i, also denoted as $\{x_i, y_i, z_i\}$; the z_i-axis is the direction of J_i.

${}^i\boldsymbol{A}_j\in\boldsymbol{R}^{3\times3}$: the rotation matrix of $\sum_j$ in relation to $\sum_i$. When $\sum_i$ is the inertia frame, the superscript i can be omitted.

$\boldsymbol{E}$, $\boldsymbol{O}$: the identity matrix and zeros matrix.

m_i, M: m_i **is the mass of** $\boldsymbol{B_i}$ and $M=\sum_{i=1}^{n} m_i$.

${}^i\boldsymbol{I}_i\in\boldsymbol{R}^{3\times3}$ (i=0, ..., n): the inertia tensor of B_i in relation to its CM, expressed in $\sum_i$.

$\boldsymbol{k}_i\in\boldsymbol{R}^3$ (i=1, ..., n): the unit vector representing the rotation direction of J_i.

$\boldsymbol{r}_i\in\boldsymbol{R}^3$($i$=1, ..., n): the position vector of C_i.

$\boldsymbol{r}_g\in\boldsymbol{R}^3$: the position vector of the system CM.

$\boldsymbol{p}_i\in\boldsymbol{R}^3$($i$=1, ..., n): the position vector of J_i.

$\boldsymbol{p}_e\in\boldsymbol{R}^3$: the position vector of the end-effector.

$\boldsymbol{a}_i$, $\boldsymbol{b}_i$, $\boldsymbol{l}_i\in\boldsymbol{R}^3$($i$=0, ..., n): the position vectors from J_i to C_i and C_i to J_{i+1}, respectively, and $\boldsymbol{l}_i=\boldsymbol{a}_i+\boldsymbol{b}_i$.

$\boldsymbol{\Theta}\in\boldsymbol{R}^n$: the joint angle vector, i.e., $\boldsymbol{\Theta}=[\boldsymbol{\theta}_1, ...,\boldsymbol{\theta}_n]$.

$\boldsymbol{v}_i$, $\boldsymbol{\omega}_i\in\boldsymbol{R}^3$: the linear and angular velocity of B_i.

$\boldsymbol{v}_0$, $\boldsymbol{\omega}_0\in\boldsymbol{R}^3$: ***the linear and angular velocity of*** B_0.

$\boldsymbol{\Psi}_b\in\boldsymbol{R}^3$: the attitude angle of the base, expressed in terms of z-y-x Euler angles, i.e.

$\boldsymbol{\Psi}_b=[\alpha_b,\beta_b,\gamma_b]^T$.

Based on Fig. 1, the position vectors of the centroid and end-effector of B_i are given respectively as follows:

$$r_i=\boldsymbol{r}_0+\boldsymbol{b}_0+\sum_{k=1}^{i-1}(\boldsymbol{a}_k+\boldsymbol{b}_k)+\boldsymbol{a}_i \tag{1}$$

$$\boldsymbol{p}_e=\boldsymbol{r}_0+\boldsymbol{b}_0+\sum_{k=1}^{n}(\boldsymbol{a}_k+\boldsymbol{b}_k) \tag{2}$$