Acta Astronautica 131 (2017) 69–82

Contents lists available at ScienceDirect

Acta Astronautica

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

Inertial parameter identification using contact force information for an unknown object captured by a space manipulator

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ARTICLE INFO

Keywords:
Space unknown object
Inertial parameter
Contact force
RLS-APSA
Identification

ABSTRACT

This paper presents a novel identification method for the intact inertial parameters of an unknown object in space captured by a manipulator in a space robotic system. With strong dynamic and kinematic coupling existing in the robotic system, the inertial parameter identification of the unknown object is essential for the ideal control strategy based on changes in the attitude and trajectory of the space robot via capturing operations. Conventional studies merely refer to the principle and theory of identification, and an error analysis process of identification is deficient for a practical scenario. To solve this issue, an analysis of the effect of errors on identification is illustrated first, and the accumulation of measurement or estimation errors causing poor identification precision is demonstrated. Meanwhile, a modified identification equation incorporating the contact force, as well as the force/torque of the end-effector, is proposed to weaken the accumulation of errors and improve the identification accuracy. Furthermore, considering a severe disturbance condition caused by various measured noises, the hybrid immune algorithm, Recursive Least Squares and Affine Projection Sign Algorithm (RLS-APSA), is employed to decode the modified identification equation to ensure a stable identification property. Finally, to verify the validity of the proposed identification method, the co-simulation of ADAMS-MATLAB is implemented by multi-degree of freedom models of a space robotic system, and the numerical results show a precise and stable identification performance, which is able to guarantee the execution of aerospace operations and prevent failed control strategies.

1. Introduction

On-orbit operation is an extremely important and highly competitive field in space technology, with frequent aerospace operations being planned for the near future. Unmanned space operation, eliminating danger to astronauts and greatly reducing operating costs, plays an indispensable role in space activities including the capture, docking, repair, and maintenance of space structures on-orbit [1]. Capturing a space unknown object by a manipulator (or space robotic arm) mounted on a free-floating spacecraft causes changes in the attitude and trajectory of the spacecraft, for the reason that there exists strong dynamic and kinematic coupling between the manipulator and the free-floating spacecraft [2]. This poses a severe challenge to the spacecraft control system's ability to satisfy the accuracy requirement for the orbit and attitude of the spacecraft, considering the uncertain properties of the captured object. To enable a precise control strategy and ensure the normal operating condition of the spacecraft, the inertial parameters (mass, centroid, inertial tensor) of the unknown object should be acquired for the sake of developing a control strategy and executing aerospace operations [3].

For identifying the inertial parameters of a space unknown object, the kinematic properties of the unknown object relative to the inertial-coordinate frame should be obtainedpreferentially. Considering the strong coupling and nonlinear characteristics of spatial parameter identification, schemes of identifying the inertial parameters of a subaerial object [4,5] become invalid. In [6], Yoshisada Murotsu proposed two parameter-identification schemes for a space unknown object based on the momentum conservation equation (MC) and equations of motion (EM) in the post-capture phase [1], which were put forward by considering the reason that the system composed of the spacecraft, manipulator and unknown object (space robotic system [1]) is not subject to external force, so it satisfies the conservation of linear or angular momentum and the conservation of internal force or moment. By acquiring the kinematic information of the system using sensors mounted in the system, the kinematics of the captured unknown object can be estimated and resolved. Kazuya Yoshida [7]

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http://dx.doi.org/10.1016/j.actaastro.2016.11.019
Received 11 March 2016; Accepted 11 November 2016
Available online 17 November 2016
0094-5765/

proposed a scheme of identifying the inertial parameters of a free-flying spacecraft using the MC method by considering the gravity gradient effect. Roberto Lampariello [8] identified the inertial parameters of a free-flying spacecraft and also an unknown object by an accelerometer mounted on the spacecraft, based on the EM method. Ou Ma [9] identified the properties of a spacecraft by changing the inertia distribution of the spacecraft system using the MC method. Thai Chau [10] proposed "adaptive reactionless motion" identification on the basis of the MC method. In the process of the capture and parameter identification, the motions of the manipulator make a minimum disturbance to the spacecraft using an adaptive reactionless control (ARLC) algorithm. Panfeng Huang [11] proposed a takeover control strategy for the unknown object during the post-capture phase by using a space robot, and the unknown property of captured object is coped with the reconfigurable control system. And methods based on vision with spacecraft-mounted cameras capturing the kinematic information of the unknown object [12,13] are also used to identify the centroid and ratios of inertia in the pre-capture phase. A tethered robotic system identifying the inertial parameters of unknown objects in the post-capture phase using the EM method is presented in [14], and the strategy of coordinated control by the orbit and attitude simultaneously for the tethered robotic system is considered in [15]. The principles mentioned above to identify the inertial parameters of a space unknown object can be divided into two categories: one based on solving for the kinematic property (linear or angular velocity) of an object by the conservation of momentum equation (MC) and the other focusing on analysing the dynamic property (accelerator or force) of an object by the equations of Newton-Euler or Lagrange (EM). Both methods have an identical nature in constructing a linear identification equation by which to estimate the intact inertial parameters and only requiring velocity measurements for the inertial parameter identification in the post-capture phase. Compared with the EM method including acceleration measurement, the MC method has superior measured data without being more susceptible to signal noise.

Generally, the unknown inertial parameters are treated as solutions of the linear identification equation [6], and the coefficients of the identification equation determine the validity of the solutions. Based on the components of the coefficient matrix or vector from the identification equation, the solutions, i.e., the inertial parameters of the unknown object, can be dominated by two factors: the kinematic property of the unknown object and the inertial property of the spacecraft and manipulator. Mainly allocated by the linear and angular velocity, the kinematic property of the unknown object can be obtained by conventional schemes including the MC and EM methods mentioned above, and the inertial property containing the mass, centroid and inertial tensor of the spacecraft and manipulator is regarded as prior knowledge. To the best knowledge of the authors, most existing reports [6–16] assume the ideal acquirement of the kinematic and inertial properties without measured or estimated errors, which does not represent the practical condition of parameter identification. In fact, with inevitable disturbances from the complicated outer space environment and uncertainties in the measurements of the sensors, the errors caused by the kinematic measurement are directly introduced to the identification equation and induce poor precision in the inertial parameters to be identified. In addition, the inertial parameters of a spacecraft are not always constant with frequent aerospace operations, e.g., fuelconsumption, and a measurement or estimation process for spacecraft is needed in the aerospace condition [7–9], which can also be accompanied by estimation error. Therefore, two errors need to be considered in the identification equation of an unknown object, including errors from the measured kinematic information of the unknown object and errors from the estimated inertial parameters of the spacecraft and manipulator. In [8], an error estimation for identifying the inertial parameters of a spacecraft is illustrated by the error-bound estimation method. However, there has been no specialized study on the influence of measurement or estimation errors on the identification precision of a captured unknown object. An analysis of the effect of errors to the identification process is essential, and a scheme is required for practical implementation.

Based on the further study in this paper, in the accumulative calculation process from the spacecraft to the end of the manipulator (end-effector), even a faint disturbance to the nominal kinematic values of a spacecraft can have an immense influence on the ultimate identification results of the unknown object. In the construction of the coefficient matrix or the vector of the identification equation by the measured information, the accumulated kinematic measurement errors and inertial estimation errors mainly account for the poor performance of parameter identification. Therefore, to weaken the accumulation of the kinematic measurement errors of the unknown object and the inertial estimation errors of the spacecraft, a straightaway mode of measurement without too much accumulation is accommodated to improve the identification accuracy. In this paper, based on the momentum theorem, information on a contact force acting on the surface of a space unknown object attached to the force/torque information of the end-effector is employed to modify the conventional identification equation, for the reason that the contact force information directly reflects the state of stress of the captured unknown object, without theoreticaldeduction by the accumulated kinematic information from the spacecraft and manipulator. The force/torque information of the end-effector has the "closest" access to the rotational motion information of the unknown object, enabling the identification of the inertial tensor of the unknown object without too much accumulated calculation. According to the momentum theorem, the increment of the linear/angular momentum of an unknown object from the MC method can be replaced by the linear/angular impulse, i.e., the integration by the resultant force or torque of the unknown object, which can be obtained by the measured information of the contact force as well as the force/torque of the end-effector. The use of the integration of the force or torque to replace the linear/angular momentum from the MC method effectively weakens the components of the calculated momentum of the unknown object in the conventional identification equation, avoiding excessive measured and estimated information from the spacecraft and thereby reducing error sources in the identification process. It is valuable to mention that the detection and application of the contact force has the feature of flexibility [17], and the detecting system incorporating the measured contact force accompanied by the force/torque of the end-effector has been adopted by many end-effectors in practice [18,19] and has been proven to be a practical and feasible measuring mode for use in aerospace operation.

In this paper, a novel identification scheme based on the contact force information of the unknown object along with the force/torque information of the end-effector is proposed, in which the calculated momentum information from the MC method is replaced by the integration of the contact force together with the force/torque of the end-effector to improve the identification precision by weakening the accumulated kinematic measurement errors of the unknown object as well as the inertial estimation errors of the spacecraft and manipulator. The innovation of the work includes the following three points: the first is a systematic analysis of the effect of the kinematic measurement errors on the identification precision of the space unknown object from the conventional method; the second is a modification of the identification equation by incorporating the contact force and force/torque information of the end-effector to improve the precision; and the third is the use of the hybrid immune algorithm of RLS-APSA to decode the modified identification equation and ensure a stable identification property.

Section 2 first describes the basic theory of identification, including the kinematics of the robotic system with an n-degree-of-freedom (n-DOF) manipulator and the conventional identification equation. Followed by a description of the process of error estimation, a systematic analysis of the effect of kinematic measurement errors on