Acta Astronautica 128 (2016) 62–71

Contents lists available at ScienceDirect

Acta Astronautica

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

Analysis and experiments for a system of two spacecraft paired by means of a flexible link

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ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form
3 June 2016
Accepted 4 July 2016
Available online 6 July 2016

Keywords:
Debris removal
Space multibody dynamics
Elastic vibrations reduction
Rest to rest control

ABSTRACT

A field of current interest in space technology is the on-orbit operation concept, often requiring that a chaser spacecraft captures a target spacecraft. The physical link connecting the two satellites is usually characterized by a high degree of flexibility, because of the special requirements imposed to the space systems, and specifically the constraints on the mass at launch. The focus of this paper is the study of an attitude control of the paired spacecraft system such that the elastic oscillations do not interfere with the attitude dynamics, and the final configuration is reached without residual vibrations. At the scope, a rest-to-rest techniques, that requires an accurate description of the dynamic model of the paired satellites as a flexible multibody setup, is applied. The results of this control are first tested by means of a numerical tool, simulating nominal and non-nominal scenarios. Then the identified control is proved in an experimental test-bed, consisting of two free-floating platforms connected by means of an elastic joint. The performance of the rest-to-rest technique is compared to other classical control laws aiming to minimally excite the system undesired dynamics, showing a promising superiority.

1. Introduction

A field of current interest in space technology is the on-orbit operation concept, that envisages the use of one active spacecraft (often called chaser) for reaching and grabbing another orbiting body (the target) for a variety of purposes, including assembling, refueling, refurbishing, and deorbiting. In these missions concepts, a physical link must be established between the chaser and the target spacecraft. This is usually accomplished by means of robotic manipulators; in some other cases, also tethers or nets have been considered [1], focusing on the vibration reduction induced by the thrust application [2] and on the coordinated attitude stabilization [3,4].

The attention of the researchers when dealing with on orbit operations of space manipulators is often focused on the interaction of the arm motion with the attitude control of the spacecraft. In some cases this motion is actively controlled by using either the attitude control reaction jets, requiring substantial amounts of propellant and limiting the useful on-orbit life of the system, or the reaction wheels, with limitations due to the saturation of these devices [5,6]. The main risk of this strategy is to lead the spacecraft into over-controlled regimes, caused by unstable feedback behavior, which can compromise the mission. In order to avoid this contingency, the spacecraft is usually left free-floating during the arm operation, by switching the attitude control off. As a consequence, it is necessary that very low reaction forces and momenta are exchanged between the arm and its base, in order to reduce the deviations from the reference attitude configuration. For example, a well-known technique that have been largely investigated in the past years [7–9] is the "Reaction Null control" that completely cancels the dynamic coupling between manipulator and spacecraft, but limits the manipulator's workspace. In order to reduce this drawback, while keeping the attitude motion as limited as possible, also minimum (not necessarily null) reaction control techniques are studied [10–13]. An example of a minimum reaction deployment is shown in Fig. 1(a), for the case of a small space shuttle equipped with a robotic arm.

A second problem that usually receives great attention is the phase of the maneuver when the manipulator has been already deployed, and the target must be grasped. During the contact between the end-effector and the grasping point, there is a risk that the target and the robot can be pushed away from each other by the contact force. One of the most studied methods to keep the exchanged forces small is the impedance control of the manipulator. When the controlled inertia characteristics of the

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http://dx.doi.org/10.1016/j.actaastro.2016.07.004
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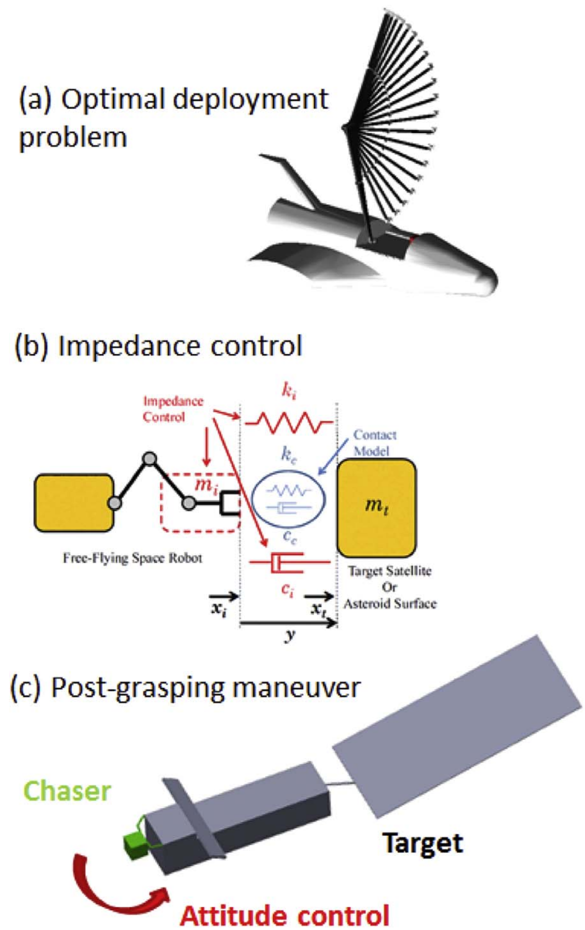

Fig. 1. Three possible fields of research related to space manipulators. This paper will focus on the post-grasping maneuvers.

end-effector match for the target mass, the manipulator can maintain contact with the target [14,15]. A conceptual explanation of the impedance control scheme is depicted in Fig. 1(b).

Differently from previous works, this paper deals with the post-grasping phase, when the goal of the chaser is the movement of the target that has been already captured, an operational phase that is seldom an object of study. Fig. 1(c) reports the case of a small chaser that must perform an attitude reorientation of a large captured target.

2. Case study description

The goal of the present work is to derive a control law in order to re-orient the combined chaser+target system from an initial to a final attitude, for example at the scope of moving a cargo module, or because a correct attitude must be acquired before re-orbiting/de-orbiting the target spacecraft [16]. Due to the special requirements imposed to the space systems, in particular the constraints on the mass at launch, the description of the system dynamics must include the elastic behavior. In fact, elastic dynamics can characterize the two satellites, because of solar panels or other appendages, as well as the manipulator (links and joints).

The resulting flexible multibody dynamics can be quite complex. Since the aim of the paper is to perform a proof of concept, a simplified model is adopted. In this sense, the manipulator is designed as a planar two-links arm; both the chaser's bus and the target are rigid bodies. All the elastic effects are modeled as a concentrated at the elbow joint, a fact that in a real scenario can be due to the presence of the motors and relevant gearboxes; a torsional spring is used to simulate (both in the mathematical model and in the experimental testbed) the behavior of the elastic joint.

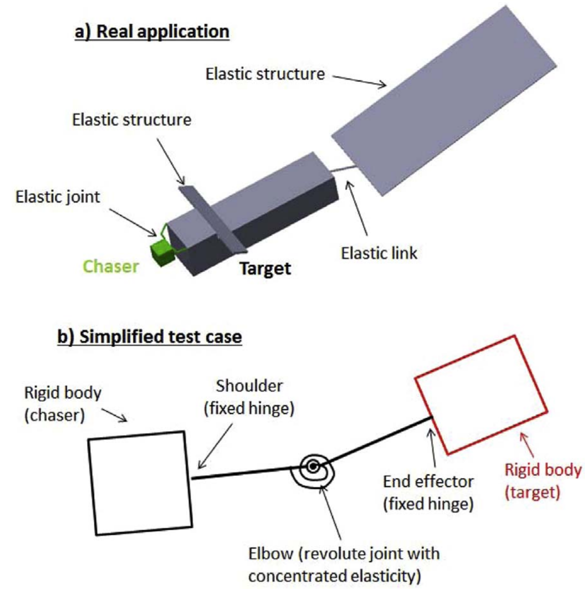

Fig. 2. The simplified model designed to test the postgrasping maneuver, compared to the real scenario.

Fig. 2 explains the simplifications performed: all the elastic effects coming from the appendages and other subsystems are considered negligible compared to the concentrated elasticity of the elbow joint. Concerning the other joints of the manipulator, both the shoulder joint and the end effector clamp to the target are considered perfect lock constraints. These strong approximations could seem as a limitation of the validity of the research to very particular cases. Indeed the proposed approach is valid for generic multibody systems, and the adopted simplifications allow for a clear insight of the problem, without loss of generality. A very low value of the elastic coefficient of the spring at the elbow joint is selected. This choice has been done in order to emphasize the problem coming from the joint elastic motion, but it can also represent a situation in which the dedicated motor is malfunctioning, and yet there is the need to complete the maneuver. In any case, the goal of achieving a small change in the elbow angle can also be seen as a reduced solicitation of the relevant motor.

The attitude control is performed by the chaser spacecraft and, if no specific actions are taken, the weak spring at the elbow joint will produce large oscillations of the target spacecraft, which would eventually prevent a correct attitude acquisition of the paired system.

One of the techniques that is widely investigated in order to prevent unwanted dynamics is the input shaping technique, which modifies the reference attitude trajectory by creating a command signal that cancels the vibration produced on the system it is applied to. Analytical details of this procedure can be found in Reference [17]. The resulting control input is a step-wise function, that in practical applications could be not easily realized. In particular the guidance, navigation and control loop sample time could be not short enough to precisely track the discontinuous input.

An alternative technique is chosen in this paper, called rest-to-rest control, and already applied to the case of flexible manipulators [18,19]. In those papers, the method aims to find the torque command that provides rest-to-rest motion in a given time for a one-link and two-link flexible arm. On-off command profiles for rest-to-rest motion of flexible systems are presented in Reference