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Dynamic/control interactions between flexible orbiting space-robot during grasping, docking and post-docking manoeuvres ☆

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ABSTRACT

Robotic systems are expected to play an increasingly important role in future space activities, such as repairing, upgrading, refuelling, and re-orbiting spacecraft. These technologies could potentially extend the life of satellites, enhance the capability of space systems, reduce the operation costs, and clean up the increasing space debris. Recent proposals for missions involving the use of space manipulators and/or automated transfer vehicles are presented as a solution for a lot of problems, which now affect the procedures and the performance of the in-orbit space systems. Other projects involving space manipulators have been developed by DARPA aiming to demonstrate several satellite servicing operations and technologies including rendez-vous, proximity operations and station-keeping, capture, docking, fluid transfer (specifically, "hydrazine"), and Orbit Replaceable Unit (ORU) transfer. Of course the dynamic coupling between the manipulator and its base mounting flexible solar arrays is very difficult to model. Furthermore, the motion planning of space robots is usually much more complicated than the motion planning of fixed-base manipulators. In this paper first of all the authors present a mixed NE/EL formulation suitable for synthesizing optimal control strategies during the deploying manoeuvres of robotic arms mounted on flexible orbiting platform (i.e. the chaser). Then two new control strategies able to compensate the flexibility excitations of the chaser satellite solar panels during the capturing of a flexible target spacecraft with the use of two robotic arms are presented and applied to a grasping manoeuvre. The mission is here divided into three main phases: the approaching, the docking and the post-grasping phase. Several numerical examples will complete the work.

1. Introduction

Manipulator systems will provide an increasingly important role in future space missions, such as repairing, re-fuelling, re-orbiting spacecraft and cleaning up the increasing space debris. Several rendez-vous and docking missions have been performed by using robotic manipulators showing the advantages of this technology such as a large working range, a high-operating speed, and a large payload to weight ratio [1]. Many studies have been performed to verify the possibility to extend the operational life of the commercial and scientific satellites through an automatic servicing spacecraft dedicated to repair, refuel and/or manage their failures [2].

Furthermore, active debris removal via robotic systems is one of the main concerns that governments and space agencies are facing in the last years [3–6]. Of course, due to

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the dynamic coupling between the manipulator and its base, the dynamics modelling and motion planning of a space robot are much more complicated than those of the fixed-base manipulators [7–9]. Moreover a very important problem concerns the elastic excitations of the solar panels during the grasping mission due to the control torques and the interactions with the target satellite that could cause the failure of the mission if not controlled. Most studies, in the past, assumed that a satellite that carries a robot arm (s) is free flying without any attitude control [10–14] and sometimes as rigid bodies. However, the satellite's attitude stabilization is necessary in most cases to retain the communication link and to generate electrical power from solar panels. A free motion should only be allowed during an operation to capture another object, which is floating free against the satellite platform. This is to avoid the unanticipated response of the satellite's attitude controller at the time of the capture. Of course it is not realistic to control the total system (satellite and its robot arms) as one dynamic system, since the number of the degrees of freedom becomes too large to be handled by mounted computers. Therefore, coordinated control of the satellite's Attitude Control System (ACS) and of the satellite-mounted robot-arm control system is necessary by taking the flexibility effects also into account. As a matter of fact to stabilize the satellite's attitude during the operation of the satellite mounted robot arm, the controls must be implemented in order to (a) control the satellite's attitude against the robotic-arm's reaction; (b) control the satellite-mounted robotic arms in order not to generate excess reaction against the satellite itself; and (c) control the robotic arm's motion without disturbing the dynamics of the flexible appendages (i.e., the solar arrays) too much. Several papers about the concept and the design of these coordinated controls when the rigid and the flexible motion interact each other were introduced by the present authors in the past [15–18]. In these papers very complex dynamics systems under the action of gravity, gravity gradient, control and disturbances forces were analyzed. Moreover suitable mathematical models of the flexibility of the space structure and their coupling with the translational and rotational motion of the robotic base platform were described. Of course after about three decades' research on these areas, some problems can be considered satisfactorily solved, but some other ones are still under development. In general, according to different control strategies of the base, a space robot may be operated in four different modes [19,20]. In the first mode (called Spacecraft Pose-Fixed Mode), the spacecraft's position and attitude are fixed using reaction jets to compensate for any dynamic forces exerted on the spacecraft generated by its manipulator. In the second mode (called Free-Flying Mode or Spacecraft Pose-Manoeuvre Mode), the spacecraft's position and attitude are controlled by thrusters to any desired values, realizing an unlimited workspace. In the third mode (called Spacecraft Attitude-Controlled Mode), the spacecraft's attitude is controlled by reaction wheels, while its translation is not. In the fourth mode (called Free-floating Mode), the spacecraft is permitted to translate and rotate freely in response to manipulator motions. In the latter case, the reaction jet fuel is conserved, and sudden motions of the end-effector due to reaction jet firing are avoided. Of course the interactive dynamics involving the base platform and the arms is a challenging task as it involves relative slewing and translational motion of the same flexible manipulator on a highly flexible platform. In [21] for instance a relatively general formulation for studying dynamics of a large class of interconnected flexible and/or rigid bodies forming a chain type topology was presented. Then in order to achieve high settling performances of the International Space Station's librational motion, when the system is subjected to induced disturbances (such as the ones created by the manoeuvers of the robotic arm), a control procedure accounting for the complexity of the model dynamics was proposed. In that procedure, a non-linear control effort was generated as a function of the generalized state composed of both rigid and flexible modes. This transformed the original highly non-linear and coupled equations of motion into a linear canonical subsystem along with a residual dynamics, required to be at least critically stable. This resulted in complete decoupling of the rigid mode dynamics, i.e., regulation of the Space Station's librational motion. In recent years, advances in control theory have provided several design techniques, which have been applied to control flexible spacecraft. Optimal and suboptimal control systems for the control of flexible spacecraft have been developed in the past [22]. More recently efforts have been also made to design robust and nonlinear control systems [23–25]. A vibration reduction of flexible solar panels by using the input shaping technique has been considered in [26], also performing experimental test when discrete on–off thrusters are used. In [27,28] a vibration control strategy for a flexible manipulator with a collocated piezoelectric sensor/actuator pair is presented. These proposed vibration controllers combine the input shaping technique with a multimode adaptive positive position feedback. Unfortunately many of these studies do not necessarily guarantee the stability of the flexible satellite's attitude motion by the robot-arm's motion. Also the flexibility and spillover issues that arise when the dynamics of the solar appendages is represented through the well-known modal superposition technique were not always properly taken into account. The goal of this work is to present two new control strategies that compensate the flexibility excitations of the chaser satellite solar panels during the capturing of a flexible target spacecraft with the use of two robotic arms. In order to prevent possible spill over or instability effects produced by the controllers a marker index related to the coupling among the modal shapes, the control gains and the dynamics of the spacecraft are introduced. This marker is able to indicate if the number of the modal shapes used to describe the elastic displacements of the space structure inside the compensation control strategy is correct or not. The mission is here divided into three main phases: the approaching, the docking and the post-grasping phase. The paper is organized as follows: in Section 2 the equation of motion for floating deployable structures is exposed; in Section 3 the chaser and the target satellite with the relevant robotic arms and flexible appendages are described; in Section 4