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# Space robots with flexible appendages: Dynamic modeling, coupling measurement, and vibration suppression

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## ABSTRACT

For a space robot with flexible appendages, vibrations of flexible structure can be easily excited during both orbit and/or attitude maneuvers of the base and the operation of the manipulators. Hence, the pose (position and attitude) of the manipulator's end-effector will greatly deviate from the desired values, and furthermore, the motion of the manipulator will trigger and exacerbate vibrations of flexible appendages. Given lack of the atmospheric damping in orbit, the vibrations will last for quite a while and cause the on-orbital tasks to fail. We derived the rigid-flexible coupling dynamics of a space robot system with flexible appendages and established a coupling model between the flexible base and the space manipulator. A specific index was defined to measure the coupling degree between the flexible motion of the appendages and the rigid motion of the end-effector. Then, we analyzed the dynamic coupling for different conditions, such as modal displacements, joint angles (manipulator configuration), and mass properties. Moreover, the coupling map was adopted and drawn to represent the coupling motion. Based on this map, a trajectory planning method was addressed to suppress structure vibration. Finally, simulation studies of typical cases were performed, which verified the proposed models and method. This work provides a theoretic basis for the system design, performance evaluation, trajectory planning, and control of such space robots.

## 1. Introduction

Space robots have been playing an important role in space activities [1]. In recent years, several free-flying space robots, which are composed of single or multiple manipulators and an unmanned platform, have been developed. The Engineering Test Satellite VII (ETS-VII) [2], launched by the National Space Development Agency of Japan (now named JAXA), demonstrated the basic technologies of rendezvous docking and space robotics. In 2007, the Orbital Express project [3], managed by the Defense Advanced Research Projects Agency, verified several satellite servicing operations and technologies including target capturing, docking, fluid transfer, and ORU (Orbit Replaceable Unit) transfer. These technologies are very important for servicing satellites in the future.

Due to dynamic coupling [4], the motion of the manipulator alters the position and attitude of the base; further, the end-effector loses its desired target pose (position and attitude) due to the motion of the base. It complicates the trajectory

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planning and control of a space robotic system. Therefore, over the past two decades, scholars have proposed several important modeling and control concepts. Ma et al. [5] derived the general dynamic equations for complex space systems and developed the MDSF (Manipulator Development and Simulation Facility), which is a good reference because it has been validated using the true flight data of space manipulators on the ISS. Umetani and Yoshida [6] presented the generalized Jacobian matrix (GJM) and resolved a motion control method. Based on the GJM, a variety of control schemes developed for a fixed-base manipulator can be extended to a space robot by only using the GJM to replace the traditional Jacobian matrix. Yoshida et al. [7] addressed the zero reaction maneuver concept and demonstrated it on the ETS-VII. Xu et al. [8] also proposed autonomous path planning and control methods to capture a non-cooperative target based on binocular stereo vision. Wang et al. [9] proposed a prediction error based adaptive Jacobian controller to deal with two kinds of uncertainties. The proposed method can be used for task-space trajectory tracking. However, it was assumed that the space manipulator moved beyond the singular area. Nanos and Papadopoulos [10] developed a methodology to avoid dynamic singularities for given end-effector trajectories. Huang et al. [11] researched the target capturing control for tethered space robots with uncertainties. Other important research achievements in space robots were well surveyed in Ref. [12]. All of the bodies of the space robots in the above works are assumed to be composed of rigid bodies.

Actually, space robot is a rigid-flexible coupling system. Both the links and joints of the manipulator installed on the space robot base are flexible parts. The flexible manipulator is a highly nonlinear and strongly-coupled dynamics system. Compared with the rigid manipulator, the dynamic modeling and control of flexible manipulator are more difficult. Many scholars in previous works focused on flexible link or flexible joint manipulators [13–15], on the ground or in space. Yang [16] designed an observer, which was able to estimate vibration, for a flexible-link manipulator based on the partial differential equation (PDE) dynamic model. Mohan and Saha [17] proposed a recursive, numerically stable simulation algorithm for serial robots with flexible links. Zi and Zhou [18] proposed a well-solved method for the prediction of dynamic response field of the crane manipulator with random and interval parameters by a hybrid uncertain model. In Ref. [19] a robust iterative learning controller was well designed to solve the trajectory tracking control of cooperative cable parallel manipulators for multiple mobile cranes. Sabatini et al. [20] designed active damping strategies to reduce the structural vibrations of a manipulator with flexible links during its on orbit operations. Masoudi and Mahzoon [21] studied a free-floating space robot with four linkages, two flexible arms, and a rigid end-effector that were mounted on a rigid spacecraft. Yang [22] proposed a novel distributed observer-based controller making the joint position track a desired trajectory and rapidly regulate vibrations on the whole beam. Ulrich et al. [23] proposed a dynamic formulation that included nonlinear effects, such as soft-windup and time-varying joint stiffness, and developed an adaptive composite control scheme for tracking the end effector of a two-link flexible-joint manipulator. Yang [24] developed a nonlinear manipulator joint model with planetary gear train and revealed the backlash and time-variant effects on positioning accuracy. Nanos and Papadopoulos [25] studied dynamics of manipulators, considering that all flexibilities were lumped at the joints and designed trajectory following controllers. Yu and Chen [26] presented the dynamics of flexible-joint manipulator. And the model including parametric uncertainties and modeling errors was used to observer-based augmented adaptive controller. In Ref. [27] a hybrid controller was proposed by combining the input shaping technique with an adaptive parameter auto disturbance rejection controller for a two-link flexible joint manipulator.

In addition, some flexible appendages [28], such as solar panels, communication antennae, and other large structures will be mounted on the base of the space robot. Correspondingly, the base is called the flexible base, and the space robot is called the flexible-base space robot. Large power consumption is generally required to complete complex or long-term on-orbit servicing tasks. Thus, long solar arrays are mounted on the spacecraft. When a space robot is applied in space, the flexible structure of it will be prone to vibration during orbit and/or attitude maneuvers of the base and the operation of the manipulators. Because there is little atmospheric damping in orbit, the generated vibration will last for quite a while, even after the motion of the base and the manipulator have stopped. It is thus very challenging to model, plan, and control such space robots. Recently, some researchers have devoted their studies to the above problems. Hirano et al. [29] developed a simple dynamic model of a space robot with a rigid manipulator and flexible appendage, and considered the coupling between the two parts using a virtual joint model. Kasai and Kojima [30] applied the input-shaping technique to control the link motion of a planar space robot equipped with a flexible appendage. Gasbarri and Pisculli [31] proposed a mixed Newton-Euler/Euler-Lagrange modeling formulation for a space robot with flexible solar arrays. Then, two control strategies based on this dynamic model were addressed to compensate for structure vibrations. Zarafshan et al. [32] derived the dynamics model by virtually partitioning the whole system into rigid and flexible portions. An adaptive hybrid suppression control algorithm was then developed. For design of the controller, the two portions were assembled to form a proper model. When the flexible-base space robot is used to capture and repair a target satellite with large flexible appendages, the dynamics and control issues are much more complex. Focusing on these issues, Xu et al. [33] developed a dynamic model and a closed-loop simulation system of a flexible-base space robot for capturing a large flexible spacecraft. Based on the dynamic simulation and analysis of different cases, several planning and control strategies for reducing the residual vibration were presented.

According to previous research, the position and attitude of the end-effector will lose the desired values due to the structure vibration of the flexible appendages. This may cause on-orbital tasks to fail and even destroy the spacecraft. Different configurations, movement trajectories, and control laws will lead to different results, and the difference can be quite large. However, the relationship between the above factors and the end-effector movement effect is still unclear. A theoretic basis is required to guide the system design, performance evaluation, trajectory planning, and motion control of

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