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On the dynamics and control of flexible joint space manipulators

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A B S T R A C T

Space manipulator systems are designed to have lightweight structure and long arms in order to achieve reduction of fuel consumption and large reachable workspaces, respectively. Such systems are subject to link flexibilities. Moreover, space manipulator actuators are usually driven by harmonic gear mechanisms which lead to joint flexibility. These types of flexibility may cause vibrations both in the manipulator and the spacecraft making the positioning of the end-effector very difficult. Here, both types of flexibilities are lumped at the joints and the dynamic equations of a general flexible joint space manipulator are derived. Their internal structure is highlighted and similarities and differences with fixed-base robots are discussed. It is shown that one can exploit the derived dynamic structure in order to design a static feedback linearization control law and obtain an exact linearization and decoupling result. The application of such controllers is desired in space applications due to their small computational effort. In case of fixed-base manipulators, the effective use of a static feedback controller is feasible only if a simplified model is considered. Then, the proposed static feedback linearization control law is applied to achieve end-effector precise trajectory tracking in Cartesian space maintaining a desirable non-oscillatory motion of the spacecraft. The application of the proposed controller is illustrated by a planar seven degrees of freedom (dof) system.

1. Introduction

In space applications, manipulator construction is different than that in terrestrial manipulators. To reduce launch mass and increase workspace, the design of lightweight and long reach manipulators is strongly preferred. However, a problem of such lightweight space manipulators is the increased structural flexibility of the links. This link flexibility causes structural vibrations, which are profound when manipulating large payloads. In addition to link flexibilities, space manipulators are also subject to joint flexibilities. Such flexibilities arise primarily due to motor torque ripples, joint transmission elements such as gears (e.g., harmonic drives), and actuator shafts.

In this paper, all system flexibilities are lumped to joint flexibilities, aiming in studying their effects in the design of control systems, and in endpoint positioning. Lumping of all flexibilities at the joint level is reasonable for systems with short links, such as the free-floating/free-flying space manipulator systems under study, or for flown systems such as the ETS-7 and the Orbital Express.

The control of flexible joint space robotic manipulators represents a very challenging problem, mainly because the number of degrees of freedom of the system is twice as the number of control inputs. In some cases, joint flexibility can lead to instability, when neglected in the control design.

In most papers, the flexibility of the robot structure is neglected. This assumption is acceptable if the robot structure is stiff enough. In space applications where lightweight structures are desired, the avoidance of flexibility effects requires very slow motions of the manipulator. However, manipulator oscillations may become evident even in very slow motions when very large payloads are handled.

Over the past decades, dynamic models of different detail level have been proposed for fixed-base manipulators with flexible joints. A simplified model, the so called *reduced* model assumes that the angular kinetic energy of the rotors of the motors is due only to their relative spinning around the driving axes (Hung and Spong, 1989). A more accurate dynamic model, called *complete*, includes also the inertial couplings existing between the motors and the links (De Luca, 1998). Each of these models has different structural properties from the point of view of control.

Several controllers have been proposed to address the flexible joint control problem for fixed-base manipulators, including techniques similar to those for rigid robots. Tomei proposes a simple PD regulator for flexible joint robots, providing simulation results for a regulation problem about a reference position (Tomei, 1991). An extension of the PD regulator for flexible joint robot

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manipulators considering also actuators dynamics as well as friction is presented by Lozano, Valera, Albetos, Arimoto, and Nakayama (1999).

A different modelling approach called singular perturbation method can be applied when the joint stiffness is relatively large, but still finite. Then, the system exhibits a two-time scale dynamic behaviour in terms of rigid and elastic variables. Using this method, one can apply controllers which consist of a slow control action designed on the basis of a rigid robot model and a fast control action designed to damp the elastic oscillations at the joints (Hung & Spong, 1989).

As mentioned above, the model structure of fixed-base manipulators with elastic joints affects the control method. The reduced model can be fully decoupled and linearized exactly by means of a nonlinear *static state feedback control law*, similarly to the well-known computed torque method for rigid manipulators (Spong, 1987). On the other hand, when considering the more complete dynamics, a satisfactory end-effector control is feasible only by applying a more complex *dynamic state feedback controller* (De Luca and Lucibello, 1998). The application of these controllers, assume the availability of both motor and link angular position and velocity as well. However, the full state measurement of the elastic joint manipulator is not usually available. In such a case, the application of observer techniques is necessary. A new observer which uses only motor position sensing, together with accelerometers suitably mounted on the links of the robot arm was introduced by De Luca, Lucibello, Schroder, and Thummel (2007). Its main advantage is that the error dynamics on the estimated state is independent from the dynamic parameters of the robot links, and can be tuned with standard decentralized linear techniques.

It is well known that the manipulator natural frequencies are continuously changing with manipulator configuration and payload (Book, 1993). Moreover, in space applications, when handling large payloads, manipulator joint or structural flexibility becomes important and can result in payload-attitude controller fuel-replenishing dynamic interactions. Such interactions may lead to control system instabilities, or manifest themselves as limit cycles (Martin, Papadopoulod, & Angeles, 1999). Therefore, the control of these systems is more sophisticated.

Martin, Papadopoulos and Angeles examined the possible dynamic interactions between the attitude controller of a spacecraft and the flexible modes of a space manipulator mounted on it (Martin et al., 1999). The authors proposed a control scheme based on on–off thrusters valves, since proportional thruster valves and thus, classical PD and PID control laws were not initially in use. Hu and Vukovich applied the singular perturbation theory in order to control the object position and internal forces as well as the joint elastic forces for a free-flying space robotic system (Hu & Vucovich, 1997). However, the proposed controller does not guarantee a non-oscillatory motion of the manipulators and their spacecraft. Ferretti et al. proposed a torque controller for a two-mass system with elastic behaviour (Ferretti, Magnani, Rocco, Viganò & Rusconi, 2005). The results show that the use of the torque sensor in the joints of the DEXARM space robot would be beneficial for the purpose of high performance motion control. More recently, Ulrich and Sasiadek addressed the problem of adaptive trajectory control of space manipulators that exhibit elastic vibrations in their joints and that are subject to parametric uncertainties and modelling errors (Ulrich & Sasiadek, 2012). In order to control the space manipulator, an inertially-stabilized platform assumption was adopted.

In this paper, we study the dynamics of space manipulators, considering all the flexibilities lumped at the joints. In terrestrial manipulators a static feedback controller, with small computational effort, can be used only if a reduced model is considered. However the reduced model is not a realistic one in most cases since it assumes that the kinetic energy of each rotor is due only to its own rotation. If a complete model is considered, then a dynamic feedback controller should be applied increasing the computational effort. Note that the computational effort is an important factor in space applications. However, using the Lagrange approach, it is shown that the structure of the dynamics of the flexible joint space manipulators differs than the model structure of the terrestrial ones. Thus, the derived model structure gives new opportunities in the design of trajectory following controllers. Therefore, exploiting the structure of the derived dynamic model, the system can be linearized and decoupled via a static feedback linearization controller reducing the computational effort. Next, the proposed controller is applied so that the end-effector follows a desired path in Cartesian space in the presence of joint flexibilities maintaining a desirable non-oscillatory motion of the spacecraft. The application of the method is illustrated by an example.

2. Dynamics of flexible joint space manipulators

This section develops the dynamic equations of a flexible joint space manipulator. We consider a system whose manipulator has revolute joints and an anthropomorphic open chain kinematic configuration for maximum reachable workspace. Under the assumption of no external forces, the system Center of Mass (CM) does not accelerate, and the system linear momentum is constant. With the further assumption of zero initial linear momentum, the system CM remains fixed in inertial space, and the origin, O, can be chosen to be the system CM, see Fig. 1.

The N joints are actuated by DC brushless motors equipped with harmonic drive mechanisms. Due to the use of the harmonic drives, all joints are considered to be flexible. When reduction gears are present, they are modelled as being placed before the joint deflection occurs, see Fig. 2.

The dynamic model of flexible manipulators requires doubling of the generalized coordinates in a Lagrangian approach, i.e. both the link and gear reduction angular position $\mathbf{q}$ and $\boldsymbol{\theta}_\mathbf{m}$, respectively. The model derivation is accomplished using the following assumptions. (i) We consider small joint deflections. Thus, the elastic and dynamic friction effects of the harmonic drive mechanism are modelled using a torsion spring of constant stiffness k and a damping element b, respectively, as shown in Fig. 2. (ii) The actuator rotors are modelled as additional rigid bodies and having their CM on the rotation axis. The motor stators are considered to be mounted on manipulator links. (iii) Since the location of the

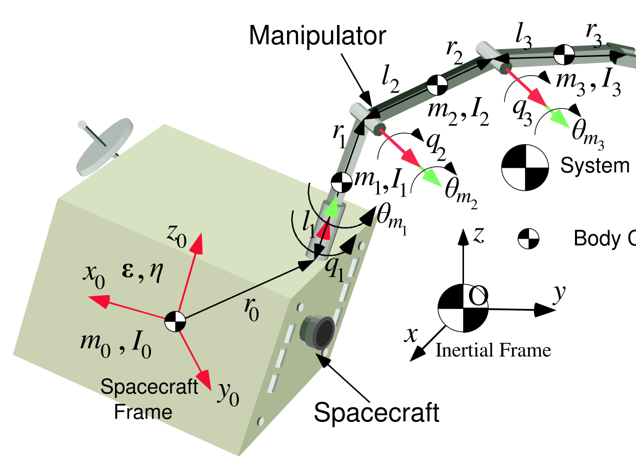

Fig. 1. A space robotic manipulator system.