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Passivity-based control of single-link flexible manipulators using a linear strain feedback

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A B S T R A C T

This work presents a new methodology for the design of a passivity-based control of single-link flexible manipulators. The control objective is the precise positioning of the link tip under large payload changes, which is achieved by combining a precise joint positioning with a link vibration damping. The main ingredients of the proposed methodology are as follows: a) a linear strain feedback is used to decouple the joint and link dynamics, b) the precise joint positioning is thus simplified to a motor controller, which is designed to be robust to joint frictions, and c) the residual tip vibrations are damped by a control designed using a passivity property between the strain measured at the base of the link and the joint velocity. Simulations and experimental results illustrated the performance of the proposed methodology.

1. Introduction

The use of flexible robots presents advantages with respect to their rigid counterparts. Some robotics applications demand lighter robots that can be driven using smaller amounts of energy. An example of this is the aerospace industry, where lightweight robot manipulators with high performance requirements (high speed operation, better accuracy) are demanded. Unfortunately, the flexibility of the arms leads to the appearance of oscillations at the tip of the links during motion. These oscillations make the precise positioning of the robot tip extremely difficult.

In order to address control objectives, such as tip-position accuracy or suppression of residual vibration, many techniques derived from the control theory have been applied to flexible robots (see, for instance, the surveys of Benosman and Vey [1] and Dwivedy and Eberhard [2] and the book of Tokhi and Azad [3]). A great number of control solutions proposed in literature are based on truncated models obtained from modal analysis (assumed modes method or finite element method). Techniques such as pole placement [4], LQG control [5] or inverse dynamics based control [6,7], achieve an acceptable tradeoff between the speed and accuracy of the tip position response and the residual vibration suppression. The drawbacks to such a model-based approach are that the complexity of the control algorithm increases significantly with the system order and the stability of the closed-loop system may be sensitive to a) changes in the robot payload, b) model parameter uncertainties and c) high-order unmodeled dynamics as the control bandwidth is raised (spillover effects).

In order to overcome the problems of the *pure* model-based approach, different kinds of controls are proposed. These controls can be classified into two groups: adaptive control [8–10], and robust controls [11–14,16,15]. Adaptive controls attempt to adapt the parameters of the controller to changes in the system, whereas robust controls are designed to be insensitive to certain variations in the system parameters. Within the second group, various solutions can be found: sliding control [11,15], neural network [12], fuzzy logic [13], teAlam:08 or H-infinity control [14], among others. These techniques usually require complex

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design methodologies. An alternative approach is to design the control from the infinite dimensional model or from the partial differential equation (PDE), such as a control based on direct strain feedback (DSFB) [17] or passivity-based control [18]. Although these techniques are robust to spillover effects and model parameter uncertainties, they present some limitations, which are briefly discussed below.

Luo [17] demonstrates that the use of DSFB is equivalent to the addition of a damping term into the PDE of the link dynamics. Consequently, DSFB together with a position control of the driving motor, which must be robust to joint frictions, can be utilized to achieve precise positioning of the arm. Nevertheless, the stability of the system depends greatly upon the motor control employed and the parameters of the link (payload) due to the fact that both are coupled. More precisely, the motor position control implemented, which is a PID controller to avoid position errors, causes a deterioration in the system response (overshoot, settling time, etc.) compared with using a PD. In addition, the tuning of the parameters is not obvious. Examples of DSFB approaches based on nonlinear strain feedbacks are [19,20]. In [19], a control law based on a joint PD controller and a nonlinear function, which depends on the joint velocity and a vibration measurement (strain, shear force or reaction force at the clamped end, or acceleration at some point of the link), is proposed. A stability analysis of this control law is carried out and only simulation results are provided for the particular case of a strain gauge placed at the base of the arm. Taking the assumption of a flexible manipulator without payload, a rigorous proof of the asymptotic stability of the closed-loop system is given in [20]. Additionally, experiments using different vibration sensors are carried out and the performance of the system is studied in depth. Nonetheless, in order to eliminate the steady state error caused by Coulomb friction, a joint PID controller is used, but the stability of the system is not studied in this case.

Other robust controls are based on certain passivity properties of flexible manipulators. Taking the motor torque as input and the velocity at the base as output (which is a passive relation), a PI controller stabilizes the system [21].The disadvantage is that the residual vibration suppression is not effective and the reference trajectory must be very slow. Wang and Vidyasagar [18] propose an alternative output, the so-called reflected tip position. It is demonstrated therein that the transfer function from the motor torque to the reflected tip velocity is passive. Therefore, a strictly passive controller makes the system stable in an L_2 sense. However, this passive relationship depends on the value of the hub inertia, which must be sufficiently small in relation to the beam inertia. Moreover, the designed controller, which is a derivative feedback of the reflected tip position error with a low pass filter, is not robust to joint frictions. Other works based on passivity which can be found in literature are, for example, [22,23]. Liu and Yuan [22] propose adding a controller that guarantees the passivity property which exists between the derivative of the reflected tip position and the motor torque so that it is not necessary to consider any restriction on the hub and the beam inertia. In addition, for a truncated model, it has been shown that a PD controller ensures the stability of the system and a desired output step response. Nevertheless, neither can the PD controller avoid the steady state error due to Coulomb friction nor can a PI controller be used to avoid it because the system becomes unobservable. Ryu, Kwon and Hannaford [23] propose a different passivity-based approach which injects variable damping without any a priori knowledge of model information. They consider the system as a two-port network, which characterizes the exchanges of energy between the trajectory generator and the plant. Therefore, they design a passivity observer and a passivity controller to make this network always passive and consequently, to make the controlled system stable. However, this technique presents two problems to be implemented in practice. Firstly, a speed controller does not eliminate the steady state error. Secondly, when the input is zero, the controller does not include any damping in the system, which leads to a less efficient cancelation of vibration than in the conventional passivity approach ([18,22]).

The objective of this work is to propose a control scheme from the partial differential equation (PDE) to alleviate: a) problems of stability for large payload variations when a control robust to joint friction is used ([17,20]), b) the problems of stability that depend on the inertia values of hub and arm ([18]), c) the steady-state error due to joint frictions ([19,18,22,23]) and d) the restrictions of using integral actions for controlling the joint angle ([18,22]). Such objective is achieved by a novel design methodology based on the passivity property between the strain measured at the base of the arm and the joint velocity, which was demonstrated in [24]. The main characteristics of the proposed methodology are as follows: a) a linear strain feedback is used to decouple the joint and link dynamics, b) the precise joint positioning is thus simplified to a motor controller, which is designed

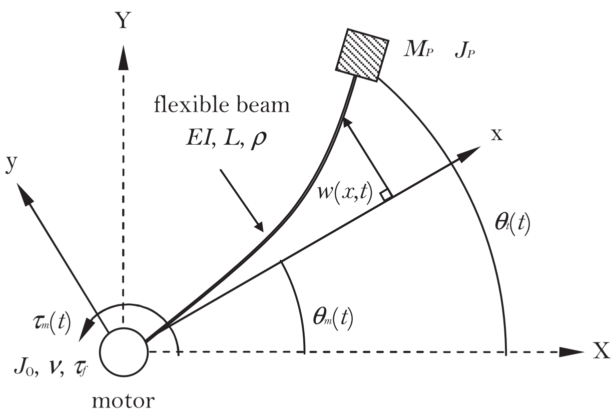

Fig. 1. Flexible arm system.