Applied Mathematical Modelling 33 (2009) 3906–3925

Contents lists available at ScienceDirect

Applied Mathematical Modelling

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

Model-based and model-free control of flexible-link robots: A comparison between representative methods

Gerasimos G. Rigatos*

Unit of Industrial Automation, Industrial Systems Institute, Stadiou Str., 26504 Rion Patras, Greece

ARTICLE INFO

Article history:
Received 14 December 2007
Received in revised form 10 January 2009
Accepted 14 January 2009
Available online 3 February 2009

Keywords:
Flexible-link robots
Inverse dynamics control
Model-free control
Energy-based control
Neural-adaptive control

ABSTRACT

The paper presents a comparative study on representative methods for model-based and model-free control of flexible-link robots. Model-based techniques for the control of flexible-link robots can come up against limitations when an accurate model is unavailable, due to parameters uncertainty or truncation of high order vibration modes. On the other hand, several research papers argue that suitable model-free control methods result in satisfactory performance of flexible-link robots. In this paper two model-free approaches of flexible-link robot control are examined: (i) energy-based control, and (ii) neural adaptive control. The performance of the aforementioned methods is compared to the inverse dynamics model-based control, in a simulation case study for planar 2-DOF manipulators.

1. Introduction

Flexible-link robots comprise an important class of systems that include lightweight arms for assembly, civil infrastructure, bridge/vehicle systems, military applications and large-scale space structures. Modelling and vibration control of flexible systems have received a great deal of attention in recent years [1–3]. The paper presents a comparative study on representative methods for model-based and model-free control of flexible-link robots (see Fig. 1). Conventional approaches to design a control system for a flexible-link robot often involve the development of a mathematical model describing the robot dynamics, and the application of analytical techniques to this model to derive an appropriate control law [4–6]. Usually, such a mathematical model consists of nonlinear partial differential equations, most of which are obtained using some approximation or simplification [1,2]. The inverse dynamics model-based control for flexible-link robots is based on modal analysis, i.e. on the assumption that the deformation of the flexible-link can be written as a finite series expansion containing the elementary vibration modes [7]. However, this inverse dynamics model-based control may result into unsatisfactory performance when an accurate model is unavailable, due to parameters uncertainty or truncation of high order vibration modes [8].

Another model-based approach for the control of flexible-link robots is flatness-based control. Flatness-based control is a powerful tool for the control of distributed parameter systems which does not follow modal analysis but the description of the flexible robot using the concept of *differential flatness* [9–11]. It has been shown that flexible-link robots and flexible beams are flat systems and thus flatness-based can be efficiently used for trajectory tracking of flexible-link manipulators [12–15]. The decomposition of the desirable trajectory into a series of a reference flat output (Gevrey function) and its derivatives enables to generate open-loop control that assures tracking of the desirable trajectory. To succeed additional

---

* Tel.: +30 694 8278397; fax: +30 2610 910297.
E-mail address: grigat@isi.gr

0307-904X/$ - see front matter © 2009 Elsevier Inc. All rights reserved.
doi:10.1016/j.apm.2009.01.012

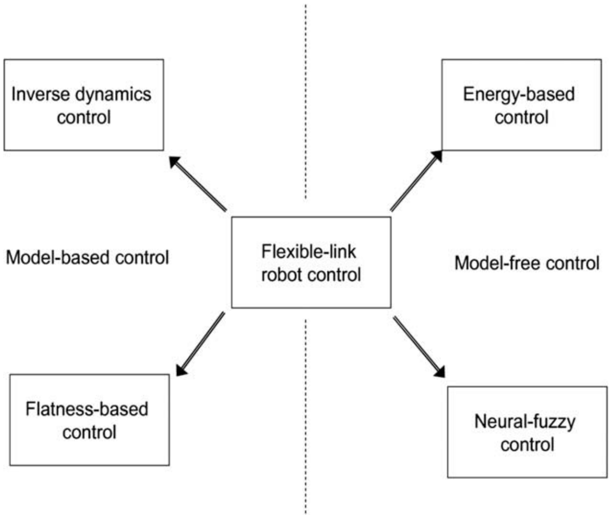

Fig. 1. Model-based and model-free control methods for flexible-link robots.

robustness a PID control loop can be designed to operate in parallel to the flatness-based controller of the flexible-link manipulator. Different model-based approaches for the control of flexible-link manipulators have been also developed. In [16] wave-based control of flexible-link robots has been proposed. First a new wave-based model of uniform mass-spring systems was introduced and next this model was used to derive a control method for flexible-link robotic systems. In [17], a survey of model-based approaches for the control of flexible-link manipulators has been given.

To overcome the inefficiencies of the aforementioned inverse dynamics control, model-free control methods have been studied [18–20]. A number of research papers employ model-free approaches for the control of flexible-link robots based on fuzzy logic and neural networks. In [21] control of a flexible manipulator with the use of a neuro-fuzzy method is described, where the weighting factor of the fuzzy logic controller is adjusted by the dynamic recurrent identification network. The controller works without any prior knowledge about the manipulator's dynamics. Control of the end-effector's position of a flexible-link manipulator with the use of a neural and a fuzzy controller has been presented in [22–24]. In [22] an intelligent optimal control for a nonlinear flexible robot arm driven by a permanent-magnet synchronous servo motor has been designed using a fuzzy neural network control approach. This consists of an optimal controller which minimizes a quadratic performance index and a fuzzy neural-network controller that learns the uncertain dynamics of the flexible manipulator. In [24] a fuzzy controller has been developed for a three-link robot with two rigid links and one flexible fore-arm. This controller design is based on fuzzy Lyapunov synthesis where a Lyapunov candidate function has been chosen to derive the fuzzy rules. In [25] a neuro-fuzzy scheme has been proposed for position control of the end effector of a single-link flexible robot manipulator. The scale factors of the neuro-fuzzy controller are adapted on-line using a neural network which is trained with an improved back-propagation algorithm. In [26] two different neuro-fuzzy feed-forward controllers have been proposed to compensate for the nonlinearities of a flexible manipulator. In [27] the dynamics of a flexible-link has been modeled using modal analysis and then an inverse dynamics fuzzy controller has been employed to obtain tracking and deflection control. In [28] a fuzzy logic controller has been applied to a flexible-link manipulator. In this distributed fuzzy logic controller the two velocity variables which have higher importance have been grouped together as the inputs to a velocity fuzzy controller while the two displacement variables which have lower importance degrees have been used as inputs to a displacement fuzzy logic controller. In [29] adaptive control for a flexible-link manipulator has been achieved using a neuro-fuzzy time-delay controller. In [30] a genetic algorithm has been used to improve the performance of a fuzzy controller designed to compensate for the links' flexibility and the joints' flexibility of a robotic manipulator.

In this paper two model-free control methods of flexible-link robots are examined and shown to be equally effective to the model-based control methods: (i) energy-based control, (ii) neural adaptive control. In the first method, instead of using the dynamical model of the links, the main stability results are derived with the use of the total energy and the energy-work relationship of the whole system [31,32]. In the second method an efficient controller based on recursive neural networks (RNN) is designed. Using the error dynamics a learning rule for the update of the RNN weights has been proposed [21,33]. It is shown that the neural controller can maintain the stability of the overall system, and can compensate for parametric uncertainties or external disturbances. It is also shown that the proposed neural-adaptive control scheme is generic since in place of the diagonal recurrent neural network, a different neural network (such as a RBF neural network) can be considered and can perform well in the suppression of the flexible-links vibrations.

The structure of the paper is as follows: In Section 2 a dynamic model for flexible-link robots is introduced and a method of model-based control is analyzed. Closed-loop stability is assured under the assumption that the truncated vibration modes do not affect the robot's dynamics. In Section 3 the control signal for the flexible links of the robot is calculated using