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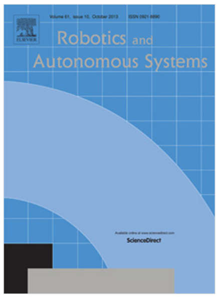

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Nonlinear State Feedback Position Control for Flexible Joint Robot with Energy Shaping

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***Abstract*— This paper presents a position control scheme for flexible joint robot (FJR). Traditional energy shaping controller with gravity compensation is revisited first and some drawbacks are analyzed; on this basis, a nonlinear state feedback controller along with energy shaping is provided, which can enhance the residual vibration suppression and reduce the overshoots of motor position. Boundedness analysis is presented and global convergence is analytically proven. Experiment results illustrate effectiveness of the proposed scheme.**

I. INTRODUCTION

"The stiffer the better" is a premise in traditional applications, especially for industrial robots that require high position precision, stability and wide bandwidth [1]. However, recently, passive elastic elements have been incorporated into the transmission system actively, known as FJR, to develop robots with suitable intrinsic characteristics [2], which also brings a new popular way to increase performance [3], for instance, low output impedance, shock tolerance, accurate force control. Besides, compliance inherent in the actuation reduces the interface stiffness with surroundings [4] on the one hand; on the other hand, this form of mechanical compliance guarantees an inertia decoupling between motor and link, thus reducing the kinetic energy involved in undesired collisions [5]. Based on the result in [6], it is known that smaller effective inertia and interface stiffness lead to safer interaction among human, robots and environment [7]. As a result, compliance has been identified as a key feature that safety-related robots should incorporate [8].

Although FJR has several advantages listed above, its position control is much more difficult. Firstly, considering elastic elements, the variables and order of dynamics increase significantly comparing with that of the rigid ones, that is, the number of control inputs is strictly less than the number of mechanical degrees of freedom, which poses a non-trivial task for controller design [9]. Secondly, the presence of compliant behavior in FJR might result in unwanted oscillations during motion and compromise system performance [5]. Furthermore, the model of FJR is highly nonlinear, and it is difficult to acquire some terms exactly [10] like friction, disturbance, etc., which are important to controller development. Moreover, mathematical model of compliant robots consists of two parts, dynamics of motor side and link side, and link side is easy to be disturbed.

Due to the control complexity and high demands for applications, position control of FJR has been regarded as one of the advanced motion control problems for next generation industrial applications [11], and it has received considerable attention during last three decades. From late 1980s to 1995, a number of theoretical methods, including modeling and control, were proposed [12] to address the issues of passive joint elasticity introduced by belts, harmonic drives and cycloidal gears in industrial robots, in which the widely used model was the simplified one proposed by Spong [13], while the most influential control law was PD controller along with gravity compensation introduced by Tomei [14], both famous for their simplification and effectiveness. Since Pratt proposed series elastic actuator (SEA) [15] in robot design, which can give back to an actuator many of the qualities that are lost in stiff ones, research on FJR (In general, robots driven by SEA can also be modeled as FJR [16], [17]) has emerged as an important topic [10], and a variety of schemes in the light of position control have been developed. Based on the controller proposed by Tomei [14], De Luca et al. developed an online gravity compensation method [18], [19], both simulation and experiment results revealed the better performance comparing with the case of constant gravity compensation. Furthermore, in order to loosen the lower bound constraint of proportional gain, Alin Albu-Schäffer et al. proposed a new approach based on energy shaping [20], which generalized results from [21] and [22], and De Luca et al. presented a control law that includes a gravity cancellation terms so as to accurately match, in any dynamics condition, the behavior of the links as if they were moving in the absence of gravity [23], [24]. In [25] and [26], a global position control method was presented, however, there is no residual vibration scheme. In [27], Gianluca Garofalo et al. developed a control law for FJR that allows to regulate the energy stored in the system to a desired value, when $H_d = 0$, it changes to be a position controller, where H_d is a storage function. To implement trajectory tracking and disturbance rejection characteristics for the link-side dynamics, a passivity based approach was proposed by adding the damping and feedforward terms to link dynamics [28], [29]. While in the seek of precise control, friction is an unignorable obstacle, thus, two kinds of methods are developed: one is to obtain friction model and serves as a compensation term, like [30], [31] and [32]; the other one is disturbance observer (DOB) based approach [10], [33]–[38]. In addition to PD based controller, other

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