*Asian Journal of Control, Vol. 8, No. 4, pp. 1-15, December 2006*

# A SURVEY ON THE CONTROL OF FLEXIBLE JOINT ROBOTS

S. Ozgoli and H. D. Taghirad

## ABSTRACT

The robotics literature of the last two decades contains many important advances in the control of flexible joint robots. This is a survey of these advances and an assessment for future developments, concentrated mostly on the control issues of flexible joint robots.

***KeyWords:*** Robot control, flexible joint robot, survey paper, modeling, singular perturbation.

## I. INTRODUCTION

The problem of position control for rigid robots is a well known and completely understood issue, and rigid manipulators are extensively used in industries [1]. The desire for higher performance from the structure and mechanical specifications of robot manipulators has spurred designers to come up with flexible joint robots (FJR)[2]. Most robots have been designed to be mechanically stiff because of the difficulty of controlling flexible members, not since rigidity, itself, is inherently attractive [3-5]. On the other hand, several new applications such as space manipulators [6] and articulated hands [7] necessitate using FJRs. In addition, as recently robots and humans have increasingly shared common spaces (especially in the fields of medicine and home automation), it has become necessary to consider the frequent physical contact between robots and humans [8]. This also necessitates considering flexibility in manipulators. Out of these necessities have emerged new control strategies, while traditional controllers used directly for FJRs have had limited performance [9,10]. Since the 1980's many attempts have been made to counter this problem, and, now, several methods have been developed. Hundreds of papers have been published on the subject of this survey paper. Among those papers, only three of them were found to be survey papers, of which two of them are specialized in two narrow categories [11,12] and only one wide survey [13] was published in 1990. After more than a decade of advancement in this area, this paper intends to summarize the new advancements and to provide an assessment for future developments. The current paper would be a complement of the mentioned survey paper [13] and its stress would be mostly on the new papers that are not covered in [13]. Besides, there are some useful insights in that paper which are not repeated here, and a new researcher is emphatically recommended to refer to that paper.

This paper is organized as follows: The next two sections (Sections 2 and 3) make the reader more familiar with the literature and concepts which are used in the following sections. Section 2 presents the modeling related issues for an FJR and section 3 describes the details of the Composite Control Method; Section 4 is devoted to the main purpose of this paper, classification of the proposed methods; and finally, a short summary and conclusions are presented in Section 5.

## II. FJR MODELING

To model an FJR the link positions are assumed to form the state vector as is the case with solid robots. Actuator positions must be also considered in the state vector, because, in contrast to solid robots, these quantities are related to the link positions through the dynamics of the flexile element. Suppose that the position of the i'th link is depicted with $\theta_i : i = 1, 2, \ldots, n$ and the position of the i'th actuator with $\theta_{i+n} : i = 1, 2, \ldots, n$. It is usual in the FJR literature to arrange these angles in a vector as follows:

$$\vec{Q} = [\theta_1, \theta_2, \ldots, \theta_n \mid \theta_{n+1}, \theta_{n+2}, \ldots, \theta_{2n}]^T = [\vec{q}_1^{\,T}, \vec{q}_2^{\,T}]^T \tag{1}$$

Using this notation and taking into account some simplifying assumptions, Spong has proposed a model for FJRs as follows [14]:

$$\begin{aligned} &I(\vec{q}_1)\,\ddot{\vec{q}}_1 + \vec{C}(\vec{q}_1, \dot{\vec{q}}_1) + K(\vec{q}_1 - \vec{q}_2) = 0 \\ &J\,\ddot{\vec{q}}_2 - K(\vec{q}_1 - \vec{q}_2) - \vec{u} = 0 \end{aligned} \tag{2}$$

where $I$ is the matrix of the link inertias and $J$ is that of the

---

Manuscript received May 5, 2004; revised March 14, 2005, accepted June 28, 2005.

The authors are with the Advanced Robotics and Automated Systems (ARAS), Department of Electrical Engineering, K.N. Toosi University of Technology, P.O. Box 16315-1355, Tehran, Iran (e-mails: ozgoli@alborz.kntu.ac.ir; taghirad@kntu.ac.ir).

motors, $\vec{C}$ is the vector of all gravitational, centrifugal and coriolis forces and torques and $\vec{u}$ is the input vector. Without loss of generality, it is assumed that all flexible elements are modeled by linear springs with the same spring constant $k$ [15] and the matrix $K = k\, I_{nxn}$.

The inertia matrices are non-singular, so the model can be changed to the following singular perturbation standard form:

$$\begin{cases} \ddot{\vec{q}} = -A(\vec{q})\,\vec{z} - G(\vec{q},\, \dot{\vec{q}}) \\ \varepsilon\,\ddot{\vec{z}} = -\big(A(\vec{q}) + B\big)\vec{z} - G(\vec{q},\, \dot{\vec{q}}) - B\vec{u} \end{cases} \tag{3}$$

in which $\vec{q} = \vec{q}_1$, $\vec{z} = K(\vec{q}_1 - \vec{q}_2)$, and $\varepsilon = 1/k$.

As seen from the model, FJRs show a two-time-scale behavior due to the presence of the small parameter ε as a multiplier on the derivative term in the second differential equation. This means that the system will have fast and slow variables. In the sequel, the authors will use the concept of integral manifold and composite control to design a suitable controller to encounter this type of special behavior [3].

## III. COMPOSITE CONTROL

It is shown in [3] that for FJRs for any given input $u_s$ there exists an integral manifold in the ($q$, $z$) space, described as follows (for simplicity the vector mark will be dropped out hereafter):

$$z_s = h(q,\, \dot{q},\, u_s,\, \varepsilon) \tag{4}$$

When the fast dynamics are asymptotically stable, the above condition, if initially violated, will be nearly satisfied after the decay of the fast transients, *i.e.* $z$ will approach to the $zs$. The unknown function $h$ can be found by solving the following partial differential equation which is obtained by substitution of $h$ and its derivatives in Eq. (3):

$$\varepsilon\,\ddot{h} = -\big(A(q) + B\big)h - G(q,\, \dot{q}) - Bu_s \tag{5}$$

This equation referred to as the manifold condition is hard to solve analytically. Spong *et al.* have proposed a method to solve this equation approximately to any order of ε by expansion of terms as will be done in Eqs. (8) and (9)[3]. Using the concept of composite control a fast term could be added to the control input to make the fast dynamics asymptotically stable:

$$u = u_s + u_f(z_f,\, \dot{z}_f) \tag{6}$$

where, $z_f = z - z_s$ represents the deviation of the fast variables from the manifold. The fast control is designed such that $u_f(0, 0) = 0$. So, on the manifold, $u = u_s$ and no modification needs to be applied on the manifold condition (5) after the addition of $u_f$. By subtracting (5) from (3) the fast dynamics can be shown to be:

$$\varepsilon\,\ddot{z}_f = -\big(A(q) + B\big)z_f - B\,u_f \tag{7}$$

Hence, a PD controller can be used to stabilize the fast dynamics. In order to solve the manifold condition and simultaneously design a corrective term to modify control performance, expansion of $h$ and $u_s$ with respect to ε can be used as follows:

$$u_s = u_0 + \varepsilon\, u_1 + \varepsilon^2\, u_2 + \ldots \tag{8}$$

$$h = h_0 + \varepsilon\, h_1 + \varepsilon^2\, h_2 + \ldots \tag{9}$$

Substituting these equations into the manifold condition and equating the terms with the same order will result in:

$$h_0 = -\frac{G(q) + B\,u_0}{A(q) + B}\,, \quad h_i = -\frac{\ddot{h}_{i-1} + B\,u_i}{A(q) + B} \tag{10}$$

By substitution of these results in the differential equation of $q$ one will reach to:

$$\ddot{q} = -\frac{B\,G(q)}{A(q) + B} + \frac{A(q)\,B}{A(q) + B}\,u_0 - A(q)\sum_{i=1}^{\infty} \varepsilon^i\, h_i \tag{11}$$

Now, if one chooses:

$$\begin{aligned} u_1 &= -\frac{\ddot{h}_0}{B} \\ u_i &= 0,\;\; i = 2,\; 3,\; \ldots \end{aligned} \tag{12}$$

then, $h_i s$ will vanish except for $h_0$ and Eq. (11) will reduce to the solid model. Therefore, using the corrective term $u_1$ has enabled us to design the $u_0$ as usual as that for solid robots. Keeping these modeling and control concepts in mind, in the next section the surveyed papers are described and classified.

## IV. THE SURVEY

### 4.1 Primary research

During the first years of considering FJRs (beginning of the 80's) several papers were published. Most of them considered the following items: 1) The necessity of considering flexibility, 2) FJR modeling, 3) Simple controller design, 4) Analysis of the FJR specifications such as controllability.

In [9,16-18] it has been shown, theoretically and empirically, that ignoring the flexibility of FJRs in controller design will result in performance degradation and bandwidth limitation. References [19,20] have ignored the coriolis and centrifugal forces, coming up with a linear model and proposing some controllers for that model, but the responses are not perfect for high velocities. In [10,21] controllability for FJRs was considered. In [22,23] a precise modeling of the joints was developed and for each joint a feedforward compensator was proposed. Reference [24] has accomplished the same task of controlling an industrial manipulator with flexibility in both joints and links. An adaptive controller based on an approximate linear model was proposed in 1986 [25]. By this time, most of the effort of researchers was focused on linear methods. For the first time, in 1986, nonlinear control methods were considered in [26]. In this paper, the authors proved that a single link FJR under static nonlinear state feedback acts like a controllable linear system, and the next year, in [27], the computed torque method, the well-known method for rigid robots, was used for a cylindrical planar FJR.

Flexibility makes an FJR act with a two time scale behavior. This leads researchers to employ the singular perturbation concept to model FJRs [16]. As said, in 1987 Spong used this concept under some simplifying assumptions to propose a feedback linearizable model for multi-link FJRs [14]. He also proposed a controller using flexible feedback linearization. This method is robust for parametric uncertainty but requires both velocity and acceleration measurements (more precisely, full state feedback). Moreover, the proposed method is computationally more complex than the same method for rigid robots. (A comparison of the feedback linearization method and the singular perturbation method has been provided in [28]). To overcome the mentioned problems, researchers have changed the principal model to a simpler model using the concept of integral manifold and they have tried to solve the resulted (manifold) condition by expansion of terms in the powers of ε and ignoring higher order terms as explained in the previous section [3,29,30]. The model shown in this way is linearizable via simple feedback, does not need rate measurements and shows a good response in simulations. After the few first years of research, more and more papers were published which will be categorized in the coming subsections.

## 4.2 Continuing the initial path

By "initial path" we mean all methods having all or several of the following specifications:

- Using a Spong model (and accepting his assumptions).
- Using the Singular Perturbation Method for modeling.
- Using the Composite Control Strategy with a fast control term to stabilize the fast variable.
- Using the concept of integral manifold and expansion in powers of ε to solve the manifold condition.

In Table 1, several papers of this category are briefly listed. For example, the reference [31] (see ninth row) is a paper which used feedback linearization for the slow term $u_s$ and a PD term as the fast control $u_f$. The terms $q$, $\dot{q}$, and $z$ must be fed back to implement the controller. A single degree of freedom manipulator with friction in both Motor and Link (M, L) bearings is used for simulations. This manipulator is modeled by a degree one ODE, in absence of gravity. The numerical values for simulation are obtained to match a real robot.

Table 1. Papers continuing the initial path.

| Code | Publication Year | Authors | Method | Control Terms | Terms to feedback | Case Study & Simulation | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | DOF | Friction | O.D.E. Degree | Gravity | Numerical Values | ε Order | Reference Input | Tracking |
| 33 | 1986 | Khorasani | Rig FBL+ IMEE+ PD(FBL) | $u_0 + \varepsilon u_1 + u_f$ | $q, dq, z$ | a degree n general model is considered with no simulation | | | | | | | |
| 14 | 1987 | Spong | Rigid FBL 1 | $u_0$ | $q$ | 1 | – | 1 | Y | Normal | | Sin(8t) | Instable |
| | | | Rigid FBL 2 | $u_0$ | $q_2$ | | | | | | | | Bad |
| | | | Flexible FBL | $u_{\text{flex}}$ | $q, dq, ddq, dddq$ | | | | | | | | Good |
| | | | Rig FBL + IMEE + PD(FBL) | $u_0 + \varepsilon u_1 + u_f$ | $q, dq, z$ | | | | | | | | Best |
| 3 | 1987 | Spong | Rigid FBL + IMEE | $u_0 + \varepsilon u_1$ | $q, dq$ | 1 | M, L | 2 | Y | SimReal | –2 | Sin(8t) | Good |
| 116 | 1989 | Zeman, Patel, Khorasani | neural network | $u$ | $q, dq, ddq$ | 1 | M, L | 2 | Y | SimReal | –3 | Sin(30t) | Good |
| 159, 111 | 1989 | Ghorbel, Hung, Spong | Rigid Adaptive + $D(z)$ | $u_{\text{rig}} + u_f$ | $q, dq, dz$ | 1 | M | 2 | Y | Real | –2 | Smoothed Step | Good |
| 110 | 1990 | Al Ashoor, Khorasani, Patel, Al-Khalili | Rig FBL (Adaptive) + IMEE (Adaptive) + Lyap(Adaptive) + PD($z$) | $u_0 + \varepsilon u_1 + u_{\text{robust}} + u_f$ | $q, dq, ?$ | 1 | M | 2 | Y | Normal | –2 | Smoothed Step | Good |
| 34 | 1993 | Al Ashoor, Patel, Khorasani | // | // | // | 2 | – | 2 | Y | Normal | –2 | Smoothed Step, Sin(t) | Good |
| 35 | 1992 | Ghorbel, Spong | Rig (Adaptive) + D($z$) + IMEE (Adaptive) | $u_0 + u_f + \varepsilon u_1 + \varepsilon^2 u_2$ | $q, dq, dz$ | 1 | M | 2 | Y | SimReal | –1 | Smoothed Step | Good |
| 31 | 1993 | Wilson, Irwin | FBL + PD | $u_s + u_f$ | $q, dq, z$ | 1 | M, L | 1 | N | SimReal | | Trapezoid | Good |
| 36 | 1995 | Ghorbel, Altpeter, Longchamp | Stability of IM + D($z$) | $\text{PD}(q)u_{ff} + u_f$ | $q, z$ | 1 | – | 2 | N | No Simulation | | | |
| 37 | 2000 | Ghorbel, Spong | Rig FBL + PD + IMEE | $u_0+u_f+\varepsilon u_1+\varepsilon^2 u_2$ | $q, dq, z$ | a degree n general model is considered with no simulation | | | | | | | |
| 38 | 2001 | Amjadi, Khadem, Khaloozadeh | fuzzy | $u_s$ | ? | 1 | M | 1 | Y | Real | –4 | Sin(t) | Good |

**Abbreviations:**

**FBL**: Feedback Linearization, **IMEE**: Integral Manifold Epsilon Expansion, **Lyap**: Lyaponov Based, **IM**: Integral Manifold.
**Normal** : Simulated with normalized values, **SimReal**: Simulated on the model of a real robot, **Real**: Implemented on a real robot.
**M**: Motor, **L**: Link, **Y**: Yes, **N**: No.
***dq***: $\dot{q}$ , ***ddq***: $\ddot{q}$ , . . .

The concepts of the Singular Perturbation Approach have also been employed with substantially different notation in [32] which originated from Russian sources. (This paper is not listed in the table due to this different notation).

In addition to the papers listed in Table 1, some other papers have continued the initial path considering robust, adaptive and some other ideas which will be categorized in the proceeding subsections appropriate to their topics (so they are not given in Table 1). The initial path has still been continued, but each of the above mentioned specifications can be disproved and removed. Spong, himself, in a joint paper with Ghorbel [35], has showed reluctance with singular perturbation because of mathematical complexity, difficulties in formation of slow control term, and bulky calculation requirements for implementation. Then, he has admired using integral manifold. Beyond this, there are some more important criticisms which will be explained in the following subsection.

### 4.3 Model promotion

In 1988 Nicosia and Tomei showed that Spong's assumption about the kinetic energy of the FJR is not satisfied in some operating conditions [39]. Two years later, the authors of [40] provided a precise model based on Lagrange dynamics without simplifying assumptions. At the same time, [41] employed Newtonian dynamics to generate a dynamical model. In this method, consideration of any coupling between link and motor, including backlash, hysteresis, nonlinear flexibility, *etc.* is possible, and modeling of nonsymmetrical dynamics of motors in order to correctly consider robot vibrations is simpler. In 1995, some other modeling points such that friction, nonlinear flexibility, kinematical errors, etc. were taken into consideration, and a more precise model than Spong's model was developed and proved to be stable [42]. In 1997, the authors of [43] disputed the assumption of weak flexibility (or large spring factor), and they showed that, for a highly flexible FJR, the proposed method of backstepping would have better results than Spong's method which causes instability for low stiffness. However, the control of highly flexible manipulators, especially with unknown varying load is still an open trend [44,45].

A precise model for Harmonic drives as the main flexible element in FJR has been considered by several researchers. Tuttle and Seering in [46] provided a rather complete nonlinear model for harmonic drive, considering kinematics error, nonlinear stiffness and friction for the system. Seyfferth, *et al.*, also provides a nonlinear model for harmonic drive, mostly concentrating on the hysteresis behavior of the compliance [47]. Taghirad and Belanger have re-examined the nonlinear dynamical models for harmonic drives in [48], and proposed a considerably simpler model for the system, in which the stiffness is found to be linear but the structural damping of the system is nonlinear. Using a frequency domain identification method, they proposed a completely linear model for the system in [49], encapsulating the nonlinear behavior of the structural damping and friction of the system into a multiplicative uncertainty model. Hence, with this approach, a linear robust controller is designed for the system, which is proven to be very effective in experiments [50,51]. Some other authors, in [52], have provided a precise model for a two link manipulator taking into account the stick-slip friction, coriolis and centrifugal forces, nonlinear flexibility, unmodeled dynamics and measurement noise. They have also provided an LQG/LTR controller for the system with favorable results in simulation [53]. Recently, the virtual work method was used to provide a dynamic model for mixed-loop planar FJR in [54]. Modeling and mode analysis of robots with simultaneous flexibility in joints and links was presented in [55]. A model that includes electrical and mechanical parts of actuator dynamics was considered in [56] and a novel nonlinear coordinate transformation has been introduced in order to exactly linearize this model. Another model including electrical dynamics of actuators (motors) and considering uncertainty was provided in [57]. A more complete version with unknown payload was provided in [58]. Reference [59] also considered actuator dynamics and proposed a disturbance-rejection control method. The key feature of this method is to transform nonlinear effects (disturbances) acting on the system to where they can be estimated and statistically compensated for. Reference [60] developed a model including a more complete model for motor dynamics including coriolis and centripetal effects.

For large gear ratios, the cross inertial effects could be ignored and Spong's model is valid. This is not the case with small gear ratios. In [61] a stabilizing controller based on a backstepping method is proposed to control a more complete model of FJR considering small gear ratios.

Precise modeling of FJRs is an open problem for researchers. The precision of a model depends on the case and conditions. A badly selected (or developed) model would impose large uncertainties which would result in poor performance or a conservative controller.

### 4.4 Various proposed controllers

During the past two decades, various methods have been proposed in order to control FJRs. In [62] an $H_2$ optimal controller based on a quadratic performance index in frequency domain was proposed. Reference [63] provided a closed form formula for optimal control of a single link FJR. The authors of [4] used feedback linearization to design a controller, and, in order to stabilize nonlinear modes of the system, they used LQR for the fast term. Feedback linearization was used in [64], too.

A method named "Pseudo Sliding Mode", with no need for rate measurements, was provided in [65]. In [66], a variable structure controller was used. Tomei has proposed using a simple PD controller [67]. In [68] it was shown that, under some limitations on the robot parameters (such as moments of inertia, *etc*.), there should be a constant controller with velocity feedback in order to stabilize fast modes. In several other papers, such as [69], state feedback has been used as well. Energy approach and min-max algorithms for controller design were developed in [70]. An extension of the energy-shaping methodology for rigid robot manipulators to the global regulator design for flexible joint manipulators (FJM) can be found in [71].

The Inverse Dynamics (or Computed Torque) Method is a well-known design method for rigid robots. Reference [72] provided an extension of the Computed Torque technique to a robot with flexible joints and electrochemical actuators. The controller was realized in continuous time. Due to drawbacks of the continuous time inverse dynamics, which were discussed in the paper, a new control strategy in discrete-time was developed in Part II of the paper [73]. This method has also been used in [74] and [75] for trajectory tracking. In [76], the same method was employed by the same author for simultaneous trajectory tracking and contact force control in a 3R spatial constrained FJR. It has been shown that, in an FJR, the acceleration level inverse dynamics equations are singular because the control torques do not have an instantaneous effect on the end-effecter contact forces and accelerations, due to the elastic media. Simultaneous position and force control was developed in [77] considering uncertainty in the model.

Intelligent controllers have been also developed for the FJRs as for other applications. Reference [78] employed a fuzzy PID controller while in [79] a Fuzzy PI controller was used. The objective in [80] is to apply a two-way fuzzy adaptive system that makes use of fuzzy sets for the identification and model-based control of an FJR. Uncertainty and inconsistency are modeled in the proposed system. In 1989 Khorasani, *et al*., claimed that using a neural network could improve the responses of FJRs [81]. References [82-84] used the benefits of neural networks to design a controller. Reference [85] provided a neural network approach which requires no off-line learning phase and no lengthy and tedious preliminary analysis to find the regression matrices. Most importantly, the uniformly ultimately bounded (UUB) stability of tracking errors and NN weights has been guaranteed. In [86], a neural network for a slow control and a linear-quadratic fast control was proposed for the control problem of a robot manipulator with flexibility both in the links and in the joints. A simple iterative learning control scheme for flexible-joint manipulators was proposed in [87] and [88] to improve tracking accuracy. Insufficient knowledge of robot dynamics and joint flexibility for precise tracking control can be overcome by using this iterative learning law as the manipulation task is repeated. This iterative learning control has been computed off-line using the link position, velocity and acceleration tracking errors. Another iterative scheme for set point regulation on a model with uncertainty was proposed in [89].

At a glance, it seems that every control method has been considered. However, from a practical point of view, a controller would be applicable only when it could cover practical requirements. Above everything else, it should be stable. Then, the uncertainties which need adaptive or robust controllers to overcome should be considered. Besides, when a practical controller is finally implemented, measurements should be feasible. In order to satisfy the aforementioned requirements, many papers have been published providing the observer based and/or adaptive and/or robust controllers that will be considered in the following subsections, respectively.

## 4.5 Measurement reduction

Reduction in the number of feedback quantities has been always a goal in controller design, especially for industrial robots including the industrial FJRs (such as PUMA 560). This is a serious problem because there are only position sensors on the link, so measurement of motor position, link velocity or motor velocity would impose extra cost. Moreover, velocity measurement would be affected by measurement noise which may not be removed by filtering [90]. The simplest approach is to use the filter $s/(s+a)$ instead of rate measurement. This was proposed in a PD configuration in [67]. It was proven in [91] that using this filter would preserve the global asymptotic stability which is one of the required specifications. The same idea (using a filter instead of rate measurement) was employed in an adaptive controller in [90,92]. In [90], to estimate link velocity from link position, a filter was used and, in order to estimate motor velocity from other states (which are motor position, link position and applied torque), an adaptive estimator was employed. Several other output feedback controllers were also proposed in [93-95].

Papers considering the number of measurements could be classified into two classes. First, some researchers have preferred to avoid rate measurement by changing the control strategy in such a way that rates would not be required essentially. For example, [96] proposed a Lyaponov based controller which needs only link position to be measured. In [97], a switching control scheme was introduced which does not uses link jerk or acceleration feedback. This scheme does not require the numerical differentiation of the velocity signal or the inversion of the inertial matrices. In [98], by mathematical manipulation of dynamics equations, the need for motor position and velocity was overcome and, instead of them, two parameters were introduced which could be estimated simply for implementation purposes. In a newer version of this paper, a simulation study with good tracking results was also provided [99]. On the other hand, some researchers [60,100,101] preferred to use observers instead of changing the control strategy, in order to reduce the number of measurements. In [102], a state feedback controller combined with an observer was proposed. References [103,104] employed the same idea using a sliding mode observer. In [105], a globally convergent observer was used assuming that position and velocity are measured. Reference [106] measured only position, but the convergence has been proven to be local. The authors then succeeded in proving pseudo local convergence, which means the convergence is local while the region of convergence could be made arbitrarily large [107]. In [108], a comparison of reduced state and full state passive control laws was made coming to the conclusion that, although reduced state feedback guarantees global asymptotic stability, it does not have good dynamic performance because it excites natural modes of the mechanical structure, contrary to the full state feedback which could impose damping to the system dynamics.

## 4.6 Adaptive controllers

The most important deficiency of the integral manifold approach is lack of robustness of parametric uncertainty [109], thus adaptive controllers have been considered since the early years in the FJR literature [110]. Ghorbel and Spong in [111] analyzed the stability of adaptive controllers for FJRs and, in [35], they implemented an adaptive version of the integral manifold method.

Adaptive methods in the FJR literature could be categorized into two major branches: the first approach, called the Inverse Dynamics Adaptive Approach, is a generalization of the Computed Torque or Inverse Dynamics Method. In this approach, the closed loop system is linearized by feedback. In the second approach, called the Slotine and Li Approach, the passivity of rigid robots is preserved by adaptive configuration for flexible robots [112-114]. In [115], a composite adaptive controller was developed for flexible joint robots with inertia parameter uncertainty. Previously published results based on the fourth-order model require at least joint jerk feedback and derivatives of the manipulator regressor (up to the second-order). In contrast, the proposed adaptive controller requires, at most, joint acceleration feedback. Its adaptive law is of the same complexity as the well-known Slotine and Li's algorithm for rigid-body robots. It should be considered that in general, FJRs are neither feedback linearizable nor passive, so the adaptive methods used for rigid robots can not be used directly for FJRs. Khorasani, in [81,5], provided the assumptions needed to change the adaptive method of rigid robots for FJRs. In this work, he provided an adaptive controller which requires velocity and acceleration measurement, then, he used a filter to overcome acceleration measurement. Another drawback for adaptive controllers for FJRs can be stated as follows: using high gain feedback in order to reduce the nonlinear effects and to accomplish fast adaptation may excite unmodeled dynamics leading the system to instability. This was considered in [116,5].

In [109], a passivity based adaptive method was proposed which requires only position and velocity feedback. The scheme presented in [117] requires augmented measurements of torque which has been done using strain gauges mounted on the joint transmission shafts. In [118] an adaptive control with arbitrary stiffness was proposed. Reference [119] provided an adaptive controller in order to generate asymptotic tracking of the link without needing a priori knowledge about flexibility. In [120], an adaptive sliding mode controller was proposed. Another adaptive sliding controller was proposed for a single-link flexible-joint robot with mismatched uncertainties in [121]. In this paper a backstepping-like design was used to deal with the mismatched problem, and the function approximation technique was employed to transform the uncertainties into finite combinations of orthonormal basis functions. In [122], an adaptive neural network controller was proposed. Another adaptive controller was developed in [123]. A stability-guaranteed adaptive controller was proposed in [124] which is an adaptive extension of the proposed controller in [125].

Spong presented the first robust adaptive control result for flexible joint robot manipulators [126]. Under the assumption of weak joint elasticity, he used a singular perturbation argument to show that adaptive control results for rigid robots may be used to control flexible joint robots provided a simple correction term is added to the control law to damp out the elastic oscillations at the joints. In this way, fundamental properties of rigid robot dynamics, such as passivity, may be exploited to design robust adaptive control laws for FJRs. An analysis of the robustness of an adaptive computed torque control for robotic manipulators, against high-frequency modes arising from flexibility, was done in [127] and another robust adaptive controller was proposed in [128].

## 4.7 Robust control and stability

Using the singular perturbation and integral manifold concepts for modeling, combined with the composite control approach, or, as stated before “the initial path”, is simple. Besides, intuitively, the use of two distinct terms for slow and fast variables seems to be very effective. These are true; however, since the global stability is not guaranteed in this method, a great deal of effort has gone into stability analysis from the beginning. Robustness of stability had been also a problem in the minds of researchers. Even, in some papers, robustness means “robust stability” and not “robust performance”. Based on this prologue, the authors of this paper have combined in this subsection all papers discussing stability, robustness of stability and/or robustness of performance. It should be also considered that in this literature stability means Uniformly Ultimately Bounded (UUB) stability [2].

In [119], an adaptive controller with proven global stability was proposed, assuming that a parametric model can be found. In [124], the stability of an adaptive controller was solved theoretically and verified by simulation and experiment. Reference [110] used composite control with a term to satisfy a Lyaponov condition for stability (see Table 1). Several controllers based on a Lyaponov stability analysis were developed in [57,77,96]. In [129], the same idea (to add a term to control) was used in a sliding mode configuration such that the added term would continuously retain state on stable trajectories. In this paper, it has been shown that, under some assumptions, the radius of the stability ball can be reduced arbitrarily. A nonlinear controller-observer scheme for the output tracking for FJRs based on a two-time-scale sliding-mode technique and a high gain estimator was presented in [130]. In this paper, a stability analysis of the resultant closed-loop system was also given. Reference [131] considered some structural properties of an n-degree-of-freedom uncertain FJR with a simple stabilizing output controller based on position measurements only for set-point regulation (in the global sense). It is well known that, in a nonlinear system, global asymptotic stability does not necessarily imply local exponential stability. This study has shown that, for the model under consideration, global asymptotic stability implies local exponential stability. Qu proposed a robust controller with local stability in [132], where he stated that is a generalization of his previous ideas about rigid robots [133,134]. Later, in [135], a robust controller was proposed with global UUB tracking in the presence of small disturbances and parametric uncertainty. Bridge and Dawson, in [136,137,42], provided robust controllers. Taghirad and Khosravi, in [138,139], stated some boundaries on the gains of a PID controller which would guarantee robustness in a composite controller structure and, based on these, proposed a PID robust composite controller [139,140]. Two more advanced versions of these works can be found in [141,142]. The authors have recently published a simpler version in which the integral manifold term has been skipped over and a new analysis and stability proof on it has been presented [143,144]. Moreover, a composite controller structure, using a linear $H_\infty$ controller for the rigid part in the presence of actuator saturation was proposed in [15]. It has been shown how actuator limitation imposes performance degradation in this framework. This work was continued in [145] where the authors added an $H_2$ performance index to the cost function to minimize the amplitude of control effort. In this manner, they designed a mixed $H_2/H_\infty$ controller which is not only robust but also needs low amplitudes of control effort. This method also shows good results in practice [2], but, as a rule of thumb, we can state that the linear robust methods will not work well and there would be a very large amount of conservativeness. This is due to the resonant behavior of the FJRs which causes large peaks in the bode plot of the linearized model of them [see the Bode plots in 15 and 145]. More recently, other robust controllers, such as a QFT controller in a composite structure [146], and a nonlinear $H_\infty$ controller [147] have been proposed by the authors. In [147], a novel idea for uncertainty description of the FJR in a norm-bounded nonlinear structure was proposed, and moreover, the tracking performance of the system is improved via a nonlinear penalty function weighting scheme which proves to be very effective in simulations. The proposed nonlinear $H_\infty$ controller possess a promising structure, which can be used for an n-link FJR, is considered a more complete nonlinear model than Spong's.

References [119,132,135,148,149] proposed robust stable controllers with full state feedback. Qu, in [133], proposed a global robust stable controller with output feedback (position and velocity) for the first time. In [150], it was shown that the nonlinear FJR model can be changed to a linear parameter varying model and a μ-synthesized controller for this model was developed. In [151], robust stability was proven for a class of time-delayed FJRs. In [152], a nonlinear $H_\infty$ controller was proposed. Some combinations of robust and adaptive approaches were proposed in [153,148,149]. A paper providing robust controller based on a neural network was also published in [82]. A simple method with PD action on the rotor position and an integral control action on the link position was shown to provide semiglobal asymptotic stability of the desired link position in [154]

## 4.8 Implementation issues

Several industrial robots have flexible joint(s) due to the use of a harmonic drive in their power transmission system. Among them, PUMA 560 and KUKA IR 160/161 could be named. The dynamics of PUMA 560 can be found in [155,156]. References [4,68] simulated their proposed methods of these dynamics. In [157], two improvements were made to the conventional rigid controller of the KUKA robot which has three flexible joints. 1) The first joint controller was redesigned, taking flexibility into account. 2) The desired trajectory was smoothed from a trapezoid shape into a ninth degree polynomial. At the end, the authors concluded that trajectory correction is more important at low speeds. Of course, this result is not general, and it must be considered that, for industrial FJRs, the spring factor is very large (of the order of $10^6$) so the robot could be said to be almost rigid; thus, only for fast motions and high performance maneuvers consideration of flexibility is essential.

In [52,53,77], a laboratory FJR was modeled and controlled. It should be considered that these results were obtained for horizontal FJRs. In horizontal FJRs, the gravity term which is the most important nonlinear, configuration variant term vanishes. So, the results on horizontal FJRs could not be extended for practical FJRs.

In [158], a PID controller was implemented on a two link FJR. References [159,109] provided the results of implementation of an adaptive controller with corrective fast term, and, in [62], an $H_2$ optimal controller was implemented on a single link FJR. Results of implementing a fuzzy supervised composite controller and an $H_2/H_\infty$ controller were published in [2]. Another implementation result was provided in [160]. In [124], an adaptive controller with guaranteed stability was proposed and the effectiveness of the proposed controller was tested experimentally.

It should be noted that many of the proposed methods which seem to be practical in the sense that they are simple, they are robust or adaptive, and they need less feedback parameters, cannot be used practically. For example, it seems that the simple controller proposed in [99] or the robust PID controller by Taghirad and Khosravi in [139] or the Qu method in [133] is practical. Qu, himself, states in [133] that, "the proposed control design is not only more attractive in practice since it requires less feedback information, but also allows the presence of significant but bounded nonlinear uncertainties". However, the size of control action is ignored in these papers. In Qu's paper we could find the control torque amplitude in a figure to be of the order of $10^9$. Taghirad considered this deficiency in his next work by Bakhshi in [15] and has used the mixed sensitivity concept to overcome it. Besides, the authors of the current paper have proposed using a fuzzy supervisory loop to remedy actuator saturation drawback for FJRs [161,162], which is a continuation to their general work on actuator saturation [163,164]. Besides these, a thorough robust stability proof of the proposed method can be found in [165,166], and results of implementation of this method can be found in [167]. In addition, it has also been shown by the authors that the mixed $H_2/H_\infty$ optimization for controller design would show attractive results for implementation [145] in presence of actuator saturation and the results of implementation for this method were published in [2].

As a conclusion, it could be said that there are some important practical aspects which are covered in the literature: stability, reduction of measurements, and considering uncertainties (by means of using adaptive or robust controllers). In addition, there are some other practical limitations which are less considered. Among them, the limitation on the control action and considering saturation nonlinearity could be named.

### 4.9 Other issues

There are some other papers about FJR control whose problem is somehow different from the problem which we have discussed so far. In [168-170], single object coordination by cooperative FJRs was considered. Reference [137] considered an FJR with two actuators in each joint, a redundancy resolution problem. Modeling and mode analysis of robots with simultaneous flexibility in joint and link was presented in [55]. References [171] and [172] also considered the same problem. A closed chain FJR was considered in [173]. The problem in [168] is the force control for FJRs. Simultaneous trajectory tracking and contact force control in a 3R spatial constrained FJR was considered in [76]. Force control could be stated to be a less considered problem.

## V. CONCLUSIONS

In this paper, the problem of modeling and control of flexible joint robots is considered and a complete survey on this problem is given. Because of space limitations, all related papers are not covered; however, all important ideas and issues related to the research path are considered and classified. It should be noted that there is an elder survey in this area [13] that this survey is a complement of and the authors of this study emphatically refer the reader to that paper. The singularly perturbed model of the system is first introduced and the composite control strategy and the concept of integral manifold are then explained briefly in order to introduce these concepts to the reader. These concepts should be known to track the remainder of the paper. Then we have tried to provide a rather complete classification of the related papers in order to make the reader familiar with the accomplished tasks in this area and the future possible developments. It is clear from the number of developments made in each topic related to FJR, that much theoretical advancement has been made in different directions, however, the technological advancement of real flexible joint manipulator and extensive use of it is still opening its path slowly into application. The existing flexible robots possessing harmonic drives in their joints are less compliant than those considered in most of the related literature. In addition, the problem of force control has also been less considered. Furthermore, design of a simple and practical position controller, considering modeling uncertainties, in the presence of practical limitations such as number of feasible measurements, actuator saturation, and online possible computations is an open area for further investigation and development.

## REFERENCES

1. Siciliano, B., "Control in Robotics: Open Problems and Future Directions," *Proc. IEEE Int. Conf. Contr. Appl.,* Conf. site??, pp. ?? (1998).
2. Ozgoli, S., "Position Control for Flexible Joint Robots in Presence of Actuator Saturation," Ph.D. Dissertation, K.N.Toosi University of Technology (2005).
3. Spong, M.W., K. Khorasani, and P.V. Kokotovic, "An Integral Manifold Approach to the Feedback Control of FJRs," *IEEE J. Rob. Autom.*, Vol. ??, No. ??, pp. ?? (1987).
4. Lin, L.C. and K. Yuan, "Control of FJRs via External Linearization Approach," *J. Rob. Syst.* (1990).
5. Khorasani, K., "Adaptive Control of FJR," *IEEE Trans. Rob. Autom.*, Vol. ??, No. ??, pp. ?? (1992).

6. Machida, K., H. Nishida, and K. Akita, "Precise Telerobotic System for Space Experiment on ETS-VII," ?? (1998).
7. Liu, H., P. Meusel, J. Butterfass, and G. Hirzinger, "DLR's Multisensory Articulated Hand. Part II: The Parallel Torque/Position Control System," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1998).
8. Nakamura, T., N. Saga, M. Nakazawa, and T. Kawamura, "Development of a Soft Manipulator Using a Smart Flexible Joint for Safe Contact with Humans," *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatron.*, Conf. Site??, Vol. 1, pp. 441-446 (2003).
9. Sweet, L.M. and M.C. Good, "Re-Definition of the Robot Motion Control Problems: Effects of Plant Dynamics, Drive System Constraints, and User Requirements," *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1984).
10. Cesareo, G. and R. Marino, "On the Controllability Properties of Elastic Robots," *Proc. Int. Conf. Anal. Optim. Syst.*, Conf. Site??, pp. ?? (1984).
11. Bridges, M.M., D.M. Dawson, and C.T. Abdallah, "Control of RLFJRs: A Survey on Backstepping Approach," *Rec. ASME Winter Ann. Meet.*, meeting site ?? (1993).
12. Brogliato, B., R. Ortega, and R. Lozano, "Global Tracking Controllers for FJMs: A Comparative Study," *Automatica*, Vol. ??, No. ??, pp. ?? (1995).
13. Spong, M.W., "The Control of FJRs: A Survey," in *New Trends and Applications of Distributed Parameter Control Systems*, G.Chen, E.B.Lee, W.Littman, L.Markus, Eds. (1990).
14. Spong, M.W., "Modeling and Control of Elastic Joint Robots," *J. Dyn. Syst., Meas., Contr.* (1987).
15. Taghirad, H.D. and Gh. Bakhshi, "Composite Hinf Controller Sythesis for FJRs," *Proc. IEEE Int. Conf. Intell. Rob. Syst.*, IROS'02, pp. 2073-2078, Lausanne, Switzerland (2002).
16. Ficola, A., R. Marino, and S. Nicosia, "A Singular Perturbation Approach to the Control of Elastic Robots," *Proc. Ann. Allerton Conf. Commun., Contr. Comput.*, Conf. Site??, pp. ?? (1983).
17. Good, M.C., K.L. Storbel, and L.M. Sweet, "Dynamics and Control of Robot Drive Systems," General Electric Company, Corporate Research and Development (1983).
18. Good, M.C., L.M. Sweet, and K.L. Storbel, "Dynamic Models for Control System Design of Integrated Robot and Drive Systems," *ASME J. Dyn. Syst. Meas., Contr.*, Vol. ??, No. ??, pp. ?? (1985).
19. Kuntze, H.B. and A. Jacubasch, "On the Closed Loop Control of an Elastic Industrial Robot," *Proc. Amer. Contr. Conf.*, Conf. Site??, pp. ?? (1984).
20. Kuntze, H.B., A. Jacubasch, J. Richalet, and C. Arber, "On the Predictive Functional Control of an Elastic Industrial Robot," *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1986).
21. Cesareo, G. and R. Marino, "On the Controllability of Elastic Robots," in *Proc. INRIA Int. Conf.*, Lecture Notes in Control and Information and Science, Springer-Verlag (1984).
22. Widmann, G.R. and S. Ahmad, "Control System Design of Robots with FJs," in *Recent Trends in Robotics: Modeling, Control and Education*. Jamshidi, Luh, Shahinpoor, Eds. (1986).
23. Widmann, G.R. and S. Ahmad, "Control of Industrial Robots with FJs," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1987).
24. Gebler, B., "Feedforward Control Strategy for an Industrial Robot with Elastic Links and Joints," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1987).
25. Tomei, P., S. Nicosia, and A. Ficola, "An Approach to the Adaptive Control of Elastic Joints Robots," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1986).
26. Marino, R. and M.W. Spong, "Nonlinear Control Techniques for Flexible Joint Manipulators," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1986).
27. Forrest-Barlach, M.G. and M. Babcock, "Inverse Dynamics Position Control of a Compliant Manipulator," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1987).
28. Spong, M.W., J.H. Hung, F. Ghorbel Bortoff, "Comparison of Feedback Linearization and Singular Perturbation for the Control of FJR," *Proc. Amer. Contr. Conf.*, Conf. Site??, pp. ?? (1989).
29. Khorasani, K. and M.W. Spong, "Invariant Manifolds and Their Application to Robot Manipulators with FJs," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1985).
30. Khorasani, K. and P.V. Kokotovic, "Feedback Linearization of a Flexible Manipulator Near its Rigid Body Manifold," *Syst. Contr. Lett.*, Vol. ??, No. ??, pp. ?? (1985).
31. Wilson, G.A. and G.W. Irwin, "Tracking Control of Manipulators with Elastic Joints," *Proc. IEEE Int. Conf. Contr. Appl.*, Conf. Site??, pp. ?? (1993).
32. Reshmin, S.A., "Control of Robots with Flexible Joints," *Proc. IEEE Conf. Decis. Contr.*, Russia, Conf. Site??, pp. ?? (2000).
33. Khorasani, K., "Feedback Control of Robots with Elastic Joints: A Geometric Approach," (1986).
34. Al Ashoor, R.A., R.V. Patel, and K. Khorasani, "Robust Adaptive Controller Design and Stability for FJM," *IEEE Trans. Syst., Man Cybern.*, Vol. ??, No. ??, pp. ?? (1993).

35. Ghorbel, F., Spong M.W., “Adaptive Integral Manifold Control of FJR Manipulators,” *Proc. IEEE Int. Conf. Rob. Autom.* (1992).
36. Ghorbel, F., F. Altpeter, and R. Longchamp, “Integral Manifold Control of a Mechanical System with a Flexible Shaft,” *Proc. Int. Conf. Recent Adv. Mechatron.*, Conf. Site??, pp. ?? (1995).
37. Ghorbel, F. and M.W. Spong, “Integral Manifold of Singularly Perturbed Systems with Application to Rigid-link FJ Multibody Systems,” *Int. J. Nonlin. Mech.*, Vol. ??, No. ??, pp. ?? (2000).
38. Amjadi, F.R., S.E. Khadem, and H. Khaloozadeh, “Position and Velocity Control of a FJR Manipulator via Fuzzy Controller Based on Singular Perturbation Analysis,” *Proc. IEEE Int. Fuzzy Syst. Conf.*, Conf. Site??, pp. ?? (2001).
39. Nicosia, S. and P. Tomei, “On the Feedback Linearization of Robots with Elastic Joints,” *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1988).
40. Readman, M.C. and P.R. Belanger, “Analysis and Control of a FJR,” *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1990).
41. Murphy, S.H., J.T. Wen, and G.N. Saridis, “Simulation and Analysis of Flexibly Jointed Manipulators,” *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1990).
42. Bridges, M.M. and D.M. Dawson, “Redesign of Robust Controllers for Rigid Link FJ Robotic Manipulators Actuated with Harmonic Drive,” *Proc. IEE - Contr. Theory Appl.*, Vol. ??, No. ??, pp. ?? (1995).
43. Oh, J.H. and J.S. Lee, “Control of FJR System by Backstepping Design Approach,” *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1997).
44. Macnab, C.J.B., G.M.T. D'Elouterio, and M. Meng, “CMAC Adaptive Control of Flexible-Joint Robots Using Backstepping with Tuning Functions,” *Proc. IEEE Int. Conf. Rob. Autom.*, Vol. 3, Conf. Site??, pp. 2679-2686 (2004).
45. Chaoui, H., P. Sicard, and A. Lakhsasi, “Reference Model Supervisory Loop for Neural Network Based Adaptive Control of a Flexible Joint with Hard Nonlinearities,” *Proc. Canadian Conf. Electri. Comput. Eng.*, Vol. 4, Conf. Site??, pp. 2029-2034 (2004).
46. Tuttle, T.D. and W.P. Seering, “A Nonlinear Model of a Harmonic Drive Gear Transmission,” *IEEE Trans. Rob. Autom.*, Vol. ??, No. ??, pp. ?? (1996).
47. Seyfferth, W., A.J. Maghzal, and J. Angeles, “Nonlinear Modeling and Parameter Identification of Harmonic Drive Robotic Transmissions,” *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1995).
48. Taghirad, H.D. and P.R. Belanger, “Modeling and Parameter Identification of Harmonic Drive Systems,” *ASME J. Dyn. Syst. Meas. Contr.*, Vol. 120, No. 4, pp. 439-444 (1998).
49. Taghirad, H.D. and P.R. Belanger, “$H_\infty$-Based Robust Torque Control of Harmonic Drive Systems,” *ASME J. Dyn. Syst. Meas. Contr.*, Vol. 123, No. 3, pp. 338-345 (2001).
50. Taghirad, H.D. and P.R. Belanger, “Robust Friction Compensation for Harmonic Drive System,” *Proc. IEEE Int. Conf. Contr. Appl.*, pp. 547-551, Trieste, Italy (1997).
51. Taghirad, H.D. and P.R. Belanger, “$H_\infty$ -Based Robust Torque Control of Harmonic Drive Systems,” *Proc. IEEE Int. Conf. Contr. Appl.*, pp. 990-994, Trieste, Italy (1997).
52. Ciuca, F., T. Lahdhiri, and H.A. Elmaraghy, “Linear Robust Motion Control of FJR, Part A: Modeling,” *Proc. Amer. Contr. Conf.* (1999).
53. Lahdhiri, T, F. Ciuca, and H.A. Elmaraghy, “Robust Linear Motion Control of FJRs, Part B: Control,” *Proc. Amer. Contr. Conf.*, Conf. Site??, pp. ?? (1999).
54. Dado, M.H.F., N.S. Al-Huniti, and A.K. Eljabali, “Dynamic Simulation Model for Mixed-Loop Planar Robots with Flexible Joint Drives,” *Mech. Machine Theory*, Vol. 36, Issue 4, pp. 547-559 (2001).
55. Li, D., J.W. Zu, and A.A. Goldenberg, “Dynamic Modeling and Mode Analysis of Flexible-Link, Flexible-Joint Robots,” *Mech. Machine Theory*, Vol. 33, Issue 7, pp. 1031-1044 (1998).
56. Tahboub, K.A. and P.C. Müller, “A Novel Model Manipulation of Elastic-Joint Robots for Control Purposes,” *Math. Comput. Simul.*, Vol. 37, Issues 2-3, pp. 221-225 (1994).
57. Ailon, A., M. Gil, E. Choi, and B. Ahn, “Stabilizing Robots with Uncertain Pareameters Actuated by DC Motors with Flexible Coupling Shafts,” *Proc. IEEE Int. Conf. Contr. Appl.*, Conf. Site??, pp. ?? (1998).
58. Ailon, A., R. Lozano, and M. Gil, “Iterative Regulation of an Electrically Driven Flexible-Joint Robot with Model Uncertainty,” *IEEE Trans. Rob. Autom.*, Vol. 16, No. 6 (2000).
59. Tahboub, K.A., “Motion Control of a Robot with Flexible Joints,” *Contr. Eng. Pract.*, Vol. 4, Issue 7, pp. 967-974 (1996).
60. Ailon, A. and R. Lozano, “Controller-Observers for Set-Point Tracking of Flexible-Joint Robots Including Coriolis and Centripetal Effects in Motor Dynamics,” *Automatica,* Vol. 32, Issue 9, pp. 1329-1331 (1996).
61. Macnab, C.J.B., G.M.T. D’Eleuterio, and M. Meng, “Using Backstepping for Control of Elastic Joint Robots with Smaller Gear Ratios,” *Proc. IEEE Canadian Conf. Electr. Comput. Eng.*, Conf. Site??, pp. ?? (1999).
62. Wang, W.S. and C.H. Liu, “Implementation of H2 Optimal Controller for a Single Link FJR,” *Proc.*

*IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1990).

63. Chen, G., "Exact Closed form Solution for Constrained Trajectory Control of Single Link FJM," *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1990).
64. Berger, R.M. and H.A. ElMaraghy, "Feedback Linearization Control of Flexible Joint Robots," *Rob. Comput. Integr. Manuf.*, Vol. 9, Issue 3, pp. 239-246 (1992).
65. Liang, F. and H.A. Elmaraghy, "Robust Control of FJR," *Proc. Canadian Conf. Electr. Comput. Eng.*, Conf. Site??, pp. ?? (1993).
66. Sira-Ramirez, H.J. and M.W. Spong, "Variable Structure Control of FJMs," *Proc. IEEE J. Rob. Autom.*, Conf. Site??, pp. ?? (1988).
67. Tomei, P., "A Simple PD Controller for Robots with Elastic Joints," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1991).
68. Readman, M.C. amd P.R. Belanger, "Stabilization of the Fast Modes of a FJR," *Int. J. Rob. Res.*, Vol. ??, No. ??, pp. ?? (1992).
69. Schaffer, A.A. and G. Hirzinger, "State Feedback Controller for FJR: A Globally Stable Approach Implemented on DLR's Light Weight Robots," *Proc. IEEE/RSJ Int. Conf. Intell. Rob. Syst.*, Conf. Site??, pp. ?? (2000).
70. Fantoni, I., R. Lozano, and A.M. Annaswamy, "Adaptive Stabilization of Underactuated FJR Using an Energy Approach and Min-Max Algorithms," *Proc. Amer. Contr. Conf.*, Conf. Site??, pp. ?? (2000).
71. Kelly, R. and V. Santibanez, "Global Regulation of Elastic Joint Robots Based on Energy Shaping," *IEEE Trans. Automat. Contr.*, Vol. 43, No. 10, pp. ?? (1998).
72. Jankowski, K.P. and H.V. Brussel, "Inverse Dynamics Task Control of Flexible Joint Robots — I: Continuous-Time Approach," *Mech. Machine Theory*, Vol. 28, Issue 6, pp. 741-749 (1993).
73. Jankowski, K.P. and H.V. Brussel, "Inverse Dynamics Task Control of Flexible Joint Robots — II: Discrete-Time Approach," *Mech. Machine Theory*, Vol. 28, Issue 6, pp. 751-762 (1993).
74. Ider, S.K. and M.K. Özgören, "Trajectory Tracking Control of Flexible-Joint Robots," *Comput. Struct.*, Vol. 76, Issue 6, pp. 757-763 (2000).
75. Ider, S.K., "Inverse Dynamics Control of Constrained Robots in the Presence of Joint Flexibility," *J. Sound Vib.*, Vol. 224, Issue 5, pp. 879-895 (1999).
76. Ider, S.K., "Force and Motion Trajectory Tracking Control of Flexible-Joint Robots," *Mech. Machine Theory*, Vol. 35, Issue 3, pp. 363-378 (2000).
77. Hu, Y.R. and G. Vukovich, "Position and Force Control of FJRs During Constrained Motion Tasks," *Mech. Machine Theory*, Vol. 36, Issue 7, pp. 853-871 (2001).
78. Malki, H.A., D. Misir, D. Feigenspan, and G. Chen, "Fuzzy PID Control of a FJR Arm with Uncertainties from Time Varying Loads," *IEEE Trans. Contr. Syst. Technol.*, Vol. ??, No. ??, pp. ?? (1997).
79. Tang, W., G. Chen, and R. Lu, "A Modified Fuzzy PI Controller for a Flexible-Joint Robot Arm with Uncertainties," *Fuzzy Sets Syst.*, Vol. 118, Issue 1, pp. 109-119 (2001).
80. Gurkan, E., I. Erkmen, and A.M. Erkmen, "Two-Way Fuzzy Adaptive Identification and Control of a Flexible-Joint Robot Arm," *Inform. Sci.*, Vol. 145, Issues 1-2, pp. 13-43 (2002).
81. Khorasani, K., "Adaptive Control of FJR," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1991).
82. Kim, H. and J.K. Parker, "Artificial Neural Network for Identification and Tracking Control of a FJ Single Link Robot," *Proc. IEEE SSST, Southeastern Symp. Syst. Theory*, Conf. Site??, pp. ?? (1993).
83. Kwan, C.M., F.L. Lewis, and Y.H. Kim, "Robust Neural Network Control of FJR," *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1995).
84. Ge, S.S. and I. Postlethwaite, "Adaptive Neural Network Controller Design for FJRs Using Singular Perturbation Technique," *IEEE Trans. Instrum. Meas. Contr.*, Vol. ??, No. ??, pp. ?? (1995).
85. Kwan, C.M., F.L. Lewis, and Y.H. Kim, "Robust Neural Network Control of Rigid Link FJRs," *Asian J. Contr.*, Vol. 1, No. 3, pp. 188-197 (1999).
86. Subudhi, B. and A.S. Morris, "Singular Perturbation Approach to Trajectory Tracking of Flexible Robot with Joint Elasticity," *Int. J. Syst. Sci.*, Vol. 34, No. 3, pp. ?? (2003).
87. Wang, D., "A Simple Iterative Learning Controller for Manipulators with Flexible Joints," *Automatica*, Vol. 31, Issue 9, pp. 1341-1344 (1995).
88. Fu, J. and N.K. Sinha, "Iterative Learning Control of Flexible-Joint Robots Using Neural Networks," *Contr. Eng. Pract.*, Vol. 1, Issue 5, pp. 882-883 (1993).
89. Ailon, A., "Output Controllers Based on Iterative Schemes for Set-Point Regulation of Uncertain Flexible-Joint Robot Models," *Automatica*, Vol. 32, Issue 10, pp. 1455-1461 (1996).
90. Lim, S.Y., D.M. Dawson, J. Hu, and M.S. de Queiroz, "An Adaptive Link Position Tracking Controller for Rigid Link FJRs without Velocity Measurements," *IEEE Trans. Syst., Man Cybern.*, Vol. ??, No. ??, pp. ?? (1997).
91. Kelly, H.J., R. Ortega, A. Ailon, and A. Loria, "Global Regulation of FJRs Using Approximate Differentiation," *IEEE Trans. Automat. Contr.*, Vol. ??,

No. ??, pp. ?? (1994).

92. Dixon, W.E., E. Zergroglu, D.M. Dawson, and M.W. Hannan, "Global Adaptive Partial State Feedback Tracking Control of Rigid Link FJR," *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatron.*, Conf. Site??, pp. ?? (1999).
93. Battilotti, S. and L. Lanari, "Global Set Point Control via Link Position Measurement for Flexible Joint Robots," *Syst. Contr. Lett.*, Vol. 25, Issue 1, pp. 21-29 (1995).
94. Nicosia, S. and P. Tomei, "A Global Output Feedback Controller for Flexible Joint Robots," *Automatica*, Vol. 31, Issue 10, pp. 1465-1469 (1995).
95. Nicosia, S. and P. Tomei, "Trajectory Tracking by Output Feedback of Flexible Joint Robots," *Contr. Eng. Pract.*, Vol. 2, Issue 5, pp. 9-12 (1994).
96. Dixon, W.E., E. Zergeroglu, M.S. de Queiroz, and D.M. Dawson, "Global Output Feedback Tracking Control for Rigid-Link Flexible-Joint Robots," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1998).
97. Mrad, F. and Sh. Ahmad, "Control of Flexible Joint Robots," *Rob. Comput. Integr. Manuf.*, Vol. 9, Issue 2, pp. 137-144 (1992).
98. Oya, M., Y. Onizuka, and K. Sato, "Robust Tracking Control of Rigid Link FJRs Using Only Joint Position and Velocity Measurements," *Proc. Int. Conf. Adv. Rob.*, Conf. Site??, pp. 385-390 (1999).
99. Oya, M. and M. Wada, "Simple Robust Tracking Controller for Rigid Link FJRs Using Only Joint Position and Velocity Measurements," *Proc. SICE Ann. Conf.*, Site??, pp. ?? (2000).
100. Ailon, A. and R. Ortega, "An Observer-Based Set-Point Controller for Robot Manipulators with Flexible Joints," *Syst. Contr. Lett.*, Vol. 21, Issue 4, pp. 329-335 (1993).
101. Nicosia, S. and P. Tomei, "State Observers for Rigid and Elastic Joint Robots," *Rob. Comput. Integr. Manuf.*, Vol. 9, Issue 2, pp. 113-120 (1992).
102. Ailon, A. and R. Lozano, "Controller-Observer for Point to Point Control of a FJR with Uncertain Parameters," *Proc. Conven. Electr. Electron. Eng.*, Israel (1995).
103. Morales, J.D.L. and J.G. Alvarez-Leal, "A Comparative Study of Speed and Position Control of a FJR Manipulator," *Proc. IEEE/RSJ Int. Conf. Intell. Rob. Syst.*, Conf. Site??, pp. ?? (1998).
104. Hernandez, J. and J.P. Barbot, "Sliding Observer-Based Feedback Control for Flexible Joints Manipulator," *Automatica,* Vol. 32, Issue 9, pp. 1243-1254 (1996).
105. Tomei, P., "An Observer for FJRs," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1990).
106. Nicosia, S. and P. Tomei, "A Method for the State Estimation of Elastic Joint Robots by Global Position Measurements," *Int. J. Adapt. Contr. Signal Process.*, Vol. ??, No. ??, pp. ?? (1990).
107. Nicosia, S. and P. Tomei, "A Tracking Controller for FJRs Using Only Link Position Feedback," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1995).
108. Sicard, P. and S.M.J. Sadr, "Comparison of Reduced State and Full State Passive Control Laws for FJR," *Proc. Canadian Conf. Electri. Comput. Eng.*, Conf. Site??, pp. ?? (1995).
109. Ghorbel, F., J.H. Hung, and M.W. Spong, "Adaptive Control of FJMs," *IEEE Contr. Syst. Mag.*, Vol. ??, No. ??, pp. ?? (1989).
110. Al Ashoor, R.A., K. Khorasani, R.V. Patel, and A.J. Al-Khalili, "Adaptive Control of FJM," *Proc. IEEE Int. Conf. Syst., Man Cybern.*, Conf. Site??, pp. ?? (1984).
111. Ghorbel, F. and M.W. Spong, "Stability Analysis of Adaptively Controlled FJM," *Proc. IEEE Conf. Decis. Contr.,* Conf. Site??, pp. ?? (1990).
112. Slotine, J.J.E. and W. Li, "Adaptive Manipulator Control: A Case Study," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1988).
113. Slotine, J.J.E. and W. Li, "On the Adaptive Control of Robot Manipulators," *Int. J. Rob. Res.*, Vol. ??, No. ??, pp. ?? (1987).
114. Benallegae, A., "Adaptive Control for Flexible-Joint Robots Using a Passive Systems Approach," *Contr. Eng. Pract.,* Vol. 3, Issue 10, pp. 1393-1400 (1995).
115. Yuan, J. and Y. Stepanenko, "Composite Adaptive Control of Flexible Joint Robots," *Automatica*, Vol. 29, Issue 3, pp. 609-619 (1993).
116. Zeman, V., R.V. Patel, and K. Khorasani, "A Neural Network Based Control Strategy for FJMs," *Proc. IEEE Conf. Decis. Contr.* (1989).
117. Chang, Y.Z. and R.W. Daniel, "On the Adaptive Control of Flexible Joint Robots," *Automatica*, Vol. 28, Issue 5, pp. 969-974 (1992).
118. Yuan, J. and Y. Stepanenko, "Adaptive Control of Flexible Joint Robots with Arbitrary Stiffness," *Contr. Eng. Pract.*, Vol. 2, Issue 5, pp. 903-906 (1994).
119. Lozano, R. and B. Brogliato, "Adaptive Control of Robot Manipulators with FJs," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1992).
120. Ge, S.S. and C.B. Besant, "Adaptive Control of FJRs," *Proc. IEEE Int. Conf. Syst., Man Cybern.*, Conf. Site??, pp. ?? (1991).
121. Huang, A.C. and Y.C. Chen, "Adaptive Sliding Control for Single-Link Flexible-Joint Robot with Mismatched Uncertainties," *IEEE Trans. Contr. Syst. Technol.*, Vol. 12, No. 5, pp. 770-776 (2004).
122. Sidi, E.Y.O., P. Sicard, D. Massicotte, and S. Lesueur,

"Adaptive High Precision Control for a FJ with Friction and Parameter Uncertainties using Neural," *Proc. Canadian Conf. Electri. Comput. Eng.*, Conf. Site??, pp. ?? (1998).

123. Ge, S.S., "Adaptive Controller Design for Flexible Joint Manipulators," *Automatica*, Vol. 32, Issue 2, pp. 273-278 (1996).
124. Kozlowski, K. and P. Sauer, "The Stability of the Adaptive Ttracking Controller of Rigid and Flexible Joint Robots," *Proc. IEEE*, Vol. ??, No. ??, pp. ?? (1999).
125. Loria, A. and R. Ortega, "On Tracking Control of Rigid and Flexible Joint Robots," *Appl. Math. Comput. Sci.*, Vol. 5, No. 2, pp. 329-341 (1995).
126. Spong, M.W., "Adaptive Control of Flexible Joint Manipulators," *Syst. Contr. Lett.*, Vol. 13, Issue 1, pp. 15-21 (1989).
127. Campion, G. and G. Bastin, "Analysis of an Adaptive Controller for Manipulators: Robustness Versus Flexibility," *Syst. Contr. Lett.*, Vol. 12, Issue 3, pp. 251-258 (1989).
128. Al-Ashoor, R.A., K. Khorasani, R.V. Patel, and A.J. Al-Khalili, "Robust Adaptive Controller Design for Flexible Joint Manipulators," *Rob. Comput. Integr. Manuf.*, Vol. 9, Issue 2, pp. 101-112 (1992).
129. Han, M.C. and Y.H. Chen, "Robust Control Design for Uncertain FJMs: A Singular Perturbation Approach," *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1993).
130. León-Morales, J.De, J.G. Alvarez-Leal, R. Castro-Linares, and Ja. Alvarez-Gallegos, "Control of a Flexible Joint Robot Manipulator via a Non-Linear Control-Observer Scheme," *Int. J. Contr.*, Vol. 74, No. 3, pp. ?? (2001).
131. Ailon, A., E. Choi, and B.H.A. Ahn, "Structural Properties of a Flexible-Joint Robot Model with Output Controllers and Some Related Applications," *Int. J. Syst. Sci.*, Vol. 31, No. 3, pp. ?? (2000).
132. Qu, Z., "Robust Control of a Class of Nonlinear Uncertain Systems with Application to FJR," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1992).
133. Qu, Z., "Input Output Robust Tracking Control Design for FJRs," *IEEE Trans. Automat. Contr.*, Vol. ??, No. ??, pp. ?? (1995).
134. Qu, Z., and D.M. Dawson, *Robust Tracking Control of Robot Manipulators*, IEEE Press, Site?? (1996).
135. Dawson, D.M., Z. Qu, M.M. Bridges, and J. Carrol, "Robust Tracking of Rigid Link FJ Elastically Driven Robot," *Proc. IEEE Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1991).
136. Martindale, S.C., M.M. Bridges, and D.M. Dawson, "Robust Position Tracking Control for Rigid Link FJR," *SSST, South-eastern Symp. Syst. Theory* (1993).
137. Bridges, M.M., D.M. Dawson, Z. Qu, and S.C. Martindale, "Robust Control of Rigid Link FJR with Redundant Joint Actuators," *IEEE Trans. Syst., Man Cybern.*, Vol. ??, No. ??, pp. ?? (1994).
138. Taghirad, H.D. and M.A. Khosravi, "Robust Stability Analysis and Studies on Composite Robust Controller for FJRs," *Proc. Iranian Conf. Electr. Eng. (in Persian)*, Conf. Site??, pp. ?? (2000).
139. Taghirad, H.D. and M.A. Khosravi, "Stability Analysis and Robust PID Design for FJR," In *Proc. 31$^{st}$ Int. Symp. Rob.*, Vol. 1, pp. 144-149, Montreal, Canada (2000).
140. Taghirad, H.D. and M.A. Khosravi, "Modeling and Robust PID Control of FJR," *Proc. Iranian Conf. Electr. Eng. (in Persian)*, Conf. Site??, pp. ?? (2000).
141. Taghirad, H.D. and M.A. Khosravi, "Stability Analysis and Robust Composite Controller Synthesis for Flexible Joint Robots," In *Proc. IEEE/RSJ Int. Conf. Intell. Rob. Syst.*, IROS'02, pp. 2067-2072, Lausanne, Switzerland (2002).
142. Taghirad, H.D. and M.A. Khosravi, "Design and Simulation of Robust Composite Controllers for Flexible Joint Robots," In *Proc. IEEE Int. Conf. Rob. Autom.*, Vol. 3, pp. 3108-3113 (2003).
143. Taghirad, H.D. and M.A. Khosravi, "A Robust Linear Controller for Flexible Joint Manipulators," In *Proc. IEEE/RSJ Int. Conf. Intell. Rob. Syst.*, IROS'04, Vol. 3, pp. 2936-2941, Japan (2004).
144. Taghirad, H.D. and M.A. Khosravi, "Robust Stability Analysis of Composite Controller Synthesis for Flexible Joint Robots," submitted to the *Int. J. Adv. Rob.* (2004).
145. Ozgoli, S. and H.D. Taghirad, "Robust Controller for Flexible Joint Robot Using $H_2/H_\infty$ and Mixed Sensitivity Approaches," *Iranian Int. Seminar Mech. Eng.*, Isfahan, Iran (2005).
146. Rahimi, H. and H.D. Taghirad, "A Composite QFT Controller for Flexible Joint Robot," submitted to *IEEE/RSJ Int. Conf. Intell. Rob. Syst.* (2004).
147. Shaterian, M. and H.D. Taghirad, "Nonlinear $H_\infty$ Controller Design for Flexible Joint Robot," submitted to *IEEE/RSJ Int. Conf. Intell. Rob. Syst.* (2004).
148. Dawson, D.M., Z. Qu, and M.M. Bridges, "Hybrid Adaptive Control for the Tracking of RLFJRs," *Rec. ASME Winter Ann. Meet.* (1991).
149. Qu, Z., D.M. Dawson, and J. Dorsey, "Exponentially Stable Trajectory Following of Robot Manipulators Under a Class of Adaptive Controls," *Automatica*, Vol. ??, No. ??, pp. ?? (1992).
150. Namerikawa, T., M. Fujita, and F. Matsumura, "Hinf Control of a Robot Manipulator Using a Linear Parameter Varying Representation," *Proc. Amer. Contr. Conf.*, Conf. Site??, pp. ?? (1997).

151. Chen, G.R., A. Desages, and P. Julian, "Trajectory Tracking and Robust Stability for a Class of Time-Delayed Flexible-Joint Robotic Manipulators," *Int. J. Contr.*, Vol. 68, No. 2, pp. ?? (1997).
152. Tomei, P., "Nonlinear $H_\infty$ Disturbance Attenuation for Robots with Flexible Joints," *Int. J. Rob. Nonlin. Contr.*, Vol. ??, No. ??, pp. ?? (1995).
153. Kim, D.H. and K. Lee, "Tracking Control Design Combined Robust and Adaptive Scheme for FJM," *Proc. IEEE Int. Conf. Contr. Appl.*, Conf. Site??, pp. ?? (1996).
154. Alvarez-Ramirez, J. and I. Cervantes, "PID Regulation of Robot Manipulators with Elastic Joints," *Asian J. Contr.*, Vol. 5, No. 1, pp. 32-38 (2003).
155. Paul, P., "Dynamics of a PUMA Manipulator," *Proc. Amer. Contr. Conf.*, Conf. Site??, pp. ?? (1983).
156. Armstrong, B., O. Khatib, and J. Burdick, "The Explicit Dynamic Model and Inertial Parameters of the PUMA 560 Arm," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1986).
157. Swevers, J., D. Torfs, M. Adams, J.D. Schutter, and H.V. Brussel, "Comparison of Control Algorithms for FJR Implemented on a KUKA IR 161/60 Industrial Robot," *Proc. IEEE Int. Conf. Adv. Rob.*, Conf. Site??, pp. ?? (1991).
158. Er, M.J., S.C. Lee, and L.L. Tan, "DSP Based Multi-rate PID Control of a Two Link FJR," *Proc. IEEE Tencon - Digital Signal Process. Appl.* (1996).
159. Ghorbel, F., J.H. Hung, and M.W. Spong, *Adaptive Control of FJM*, *IEEE Computer Society*, Site?? (1989).
160. Dixon, W.E., E. Zergroglu, D.M. Dawson, and M.W. Hannan, "Experimental Video of a Controller for FJR," *Proc. IEEE/ASME Int. Conf. Adv. Intell. Mechatron.* (1999).
161. Ozgoli, S. and H.D. Taghirad, "Design of Composite Control for Flexible Joint Robots with Saturating Actuators," In *Proc. IEEE Conf. Mechatron. Rob.*, pp. 483-488, Aachen, Germany (2004).
162. Ozgoli, S. and H.D. Taghirad, "Using Fuzzy Logic to Remedy Actuator Saturation in a Composite Controller for Flexible Joint Robot," In *Proc. 5th Iranian Conf. Fuzzy Syst.*, Tehran, Iran, pp. ?? (2004).
163. Ozgoli, S. and H.D. Taghirad, "Fuzzy Logic Supervisory Loop to Remedy Actuator Saturation Drawbacks," In *Proc. 16th Int. Conf. Syst. Eng.*, pp. 537-541, Coventry University, England (2003).
164. Ozgoli, S. and H.D. Taghirad, "Preventing Actuator Saturation Using a Fuzzy Supervisory Loop," In *Proc. 5th Conf. Intell. Syst.*, Mashhad University, Iran, pp. ?? (2003).
165. Ozgoli, S. and H.D. Taghirad, "Robust Control of FJRs with a Supervisory Control Loop to Remedy Actuator Saturation," In *Proc. Iranian Conf. Electr. Eng.*, Zanjan, pp. ?? (2005).
166. Ozgoli, S. and H.D. Taghirad, "Robust Stability Analysis of FJR Composite Controller with a Supervisory Loop," In *Proc. IROS05, IEEE/RSJ Int. Conf. Intell. Rob. Syst.*, Edmonton, Canada, pp. ?? (2005).
167. Taghirad, H.D. and S. Ozgoli, "Robust Controller with a Supervisor Implemented on a Flexible Joint Robot," In *Proc. CCA05, IEEE Int. Conf. Contr. Appl.*, Toronto, Canada, pp. ?? (2004).
168. Ahmad, S., "Control of Cooperative Multiple FJRs," *Proc. IEEE Int. Conf. Decis. Contr.*, Conf. Site??, pp. ?? (1991).
169. Jing, Z. and B. Shi-Xian, "The Study of Coordinated Manipulation of Two Redundant Robots with Elastic Joints," *Mech. Machine Theory,* Vol. 35, Issue 7, pp. 895-909 (2000).
170. Xie, H., I.J. Bryson, F. Shadpey, and R.V. Patel, "A Robust Control Scheme for Dual Arm Redundant Manipulators: Experimental Results," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1999).
171. Yang, J.H. and L.C. Fu, "Analysis and Control for Manipulators with both Joint and Link Flexibility," *Proc. IEEE Int. Conf. Rob. Autom.*, Conf. Site??, pp. ?? (1993).
172. De Luca A. and S. Panzieri, "Learning Gravity Compensation in Robots: Rigid Arms, Elastic Joints, Flexible Links," *Int. J. Adapt. Contr. Signal Process.*, Vol. ??, No. ??, pp. ?? (1993).
173. Hu, Y.R. and G. Vukovich, "Modeling and Control of Free Flying FJ Coordinated Robots," *Proc. IEEE Int. Conf. Adv. Rob.*, Vol. ??, No. ??, pp. ?? (1997).

**Sadjaad Ozgoli** received his B.Sc. and M.Eng degrees in electrical engineering from Sharif University of Technology, Tehran, Iran, respectively in 1997 and 1999. He received his Ph.D. from K.N. Toosi University of Technology, Tehran, Iran in electrical engineering with minors in mechanical engineering in 2005. He has published more than 15 papers in international journals and conference proceedings. He works on control systems applied on Mechatronics systems.

**Hamid D. Taghirad.** received his B.Sc. degree in mechanical engineering from Sharif University of Technology, Tehran, Iran, in 1989, his M.Eng in mechanical engineering in 1993, and his Ph.D. in electrical engineering in 1997, both from McGill University, Montreal, Canada. He is currently an Associate Professor with the Control Group at the Electrical Engineering Department, and the Director of the Advanced Robotics and Automated System (ARAS) research center at K.N. Toosi University of Technology, Tehran, Iran. His publications include two books, and more than 80 papers in international Journals and conference proceeding, and his research interests are robust and nonlinear control applied on the robotic systems.