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Design of Composite Control For Flexible Joint Robots With Saturating Actuators

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ABSTRACT
In this paper a method of controller design for FJRs considering actuator saturation and other practical limitations is proposed. In the proposed method the need of powerful actuator is skipped over by decreasing the bandwidth of the fast controller during critical times. In order to accomplish this, a supervisory control is employed which uses fuzzy logic to adjust the proper forward path gain. This prevents instability caused by saturation without a great change in performance. All other practical considerations to make the controller implementable are taken into account and finally the performance of the proposed controller is verified through simulation.

Keywords: Flexible Joint Robot, Actuator Saturation, Supervisory Control, Fuzzy Logic.

Introduction

The desire for higher performance from the structure and mechanical specifications of robot manipulators has been spurred designers to come up with flexible joint robots (FJR). Several new applications such as space manipulators [1] and articulated hands [2] necessitate using FJRs. This necessity has emerged new control strategies needed, while the traditional controllers used for FJRs have failed in performance [3,4]. Since 1980's many attempts has been made to encounter this problem and now, several methods has been proposed including various linear, nonlinear, robust, adaptive and intelligent controllers [5,6]. Among these, only a few researchers have been considered practical limitations, for example, actuator saturation as a real practical drawback to achieve a good performance has become limited attention [7].

On the other hand actuator saturation has been considered by the control community from early achievements of control engineering. During 50's and 60's at the beginning era of optimal control, researchers have been working on saturation, introducing bang-bang control methods. Over the last decade the control research community has shown a new interest in the study of the effects of saturation on the performance of systems. In fact it can be said that in the past, researchers were encountered a *drawback* identified as actuator saturation and developed methods to avoid it, while now, researchers develop methods to achieve a desirable performance in the presence of actuator saturation seen as a *limitation*.

It can be said that saturation may cause two types of performance degradations: 1) Inevitable limitations such as slow responses, undesirable transitions, etc. 2) Removable problems such as instability, bad steady state performance, etc. The goal in considering saturation at design step is to decrease or remove the latter. A common classical remedy for systems with bounded control is to reduce the bandwidth of the control system such that saturation seldom occurs. This is a trivial weak solution because even for small commands and disturbances, the possible performance of the system is degraded. This idea (reduction in bandwidth by reduction in the closed loop gain) is practical and "easy", so this motivates some researchers to propose an "adaptive" reduction in bandwidth consistent with the actuation levels [8]. The "adaptation" process is done under supervision of a *supervisory loop*, and as proposed in [8] is accomplished through complex computations which practically seems not to be implementable. In order to come up with an online implementable controller for FJRs, in this paper a fuzzy logic supervisory control is proposed. In this manner, the fuzzy logic is set to be "out of the main loop", at a supervisory level, at the aim of preserving the essential properties of the main controller. This idea is first.

published by the authors in [9] and is modified to use with composite controller for FJRs in this paper. It is shown that a model free implementable supervisory control can be embedded in a composite control structure to cope with actuator saturation.

This paper is organised as follows: Section 2 presents the modelling procedure for an FJR; Section 3 describes the details of the composite control method; Section 4 is devoted to description of the new method; Section 5 is allocated for simulation studies and finally, the conclusions are presented in Section 6.

FJR Modeling

To model an FJR the link positions are let to be in the state vector as is the case with solid robots. Actuator positions must be also considered because in contradiction to solid robots these are related to the i'th position through the dynamics of the flexile element. When the position of the i'th link is shown with $\theta_i : i = 1,2,...,n$ and the position of the i'th actuator with θ_{i+n} : i=1,2,…,n , It is usual in the FJR literature to arrange these angles in a vector as follows:

$$\bar{Q} = [\theta_1, \theta_2, ..., \theta_n, \theta_{n+1} \mid \theta_{n+2}, ..., \theta_{2n}]^T = [\bar{q}_1^{\,T}, \bar{q}_2^{\,T}]^T \qquad (1)$$

Using this notation and taking into account some simplifying assumptions, spong has proposed a model for FJRs [10] as follows:

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

where I is the matrix of the link inertias and J is that of the motors, C is the vector of all gravitational, centrifugal and coriolis forces and torques and u is the input vector. Further without loss of generality [11] it is assumed that all flexible elements are modelled by linear springs with the same spring constant k and the matrix $K = k\, I_{3x3}$.

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

$$\begin{aligned} &\ddot{\bar{q}} = -A(\bar{q})\,\bar{z} - G(\bar{q}, \dot{\bar{q}}) \\ &\varepsilon\,\ddot{\bar{z}} = -(A(\bar{q}) + B(\bar{q}))\bar{z} - G(\bar{q}, \dot{\bar{q}}) - B(\bar{q})\bar{u} \end{aligned} \qquad (3)$$

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

As seen from the model, FJRs show a two-time-scale behaviour due to the presence of the small parameter ε as a multiplier on derivative term in the second differential equation. This means that the system will have fast and slow variables. In the sequel we will use the concept of integral manifold and composite control to design a suitable controller with this requirement [11].

Composite control

It is shown in [11] that for FJRs for any given input u_s there exists an integral manifold in the (q, z) space, described as follows:

$$z_s = h(q_1, \dot{q}_1, u_s, \varepsilon) \tag{4}$$

When the fast dynamics are asymptotically stable, the above condition, if violated initially, will be nearly satisfied after the decay of the fast transients, i.e. z will approach to the z_s. 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 equation (3):

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

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 done in equations (8) and (9) [11]. Using the concept of composite control [12] a fast term could be added to the control input to make the fast dynamics to be 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 any modification is needed to be applied on manifold condition (5). By subtracting (5) from (3) the fast dynamics can be shown to be:

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

So a PD controller can be used to stabilize the fast dynamics. To solve the manifold condition and simultaneously to design a corrective term in the controller, expansion of h and u_s can be used as follows:

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

$$h = h_0 + \varepsilon h_1 + \varepsilon^2 h_2 + \dots \tag{1}$$

substituting these in the manifold condition and equating the terms with the same order will result in:

$$h_0 = -\frac{G(q)+B(q)u_0}{A(q)+B(q)}, \quad h_i = -\frac{\ddot{h}_{i-1} + B(q)u_i}{A(q)+B(q)} \tag{2}$$

by substitution of these results in the differential equation of q we will have:

$$\ddot{q} = -\frac{B(q)G(q)}{A(q)+B(q)} + \frac{A(q)B(q)}{A(q)+B(q)}u_0 - A(q)\sum_{i=1}^{\infty} \varepsilon^i h_i \tag{3}$$

now if we choose

$$u_1 = -\frac{\ddot{h}_0}{B(q)} \tag{4}$$

$$u_i = 0, \quad i = 2,3,\dots$$

then the h_is will vanish except for h_0 and equation (11) will reduce to the solid model. So using the corrective term u_1 will enable us to design the u_0 as usual as that for solid robots.

Using a simple PD controller for the u_0 has the benefits: 1) no need for rate measurements, 2) no need for offline computations (specially derivations of the reference input) 3) guaranteed robust stability by the conditions detailed in [13], the three main requests for implementation purposes.

The overall control system for an FJR using composite control with a corrective term is shown in figure 1 by which very good performance can be achieved in the expense of high actuator effort. This is mainly remedied in this paper and will be explained in the next section.

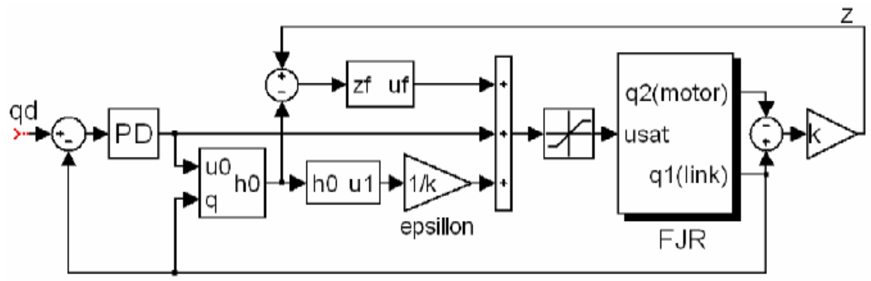

Figure 1: The FJR control system

The Supervisory loop

In this part we will first describe the idea of error governor as it is first proposed by the authors [9]. Then the developments needed to use it with the FJR model are elaborated. Without loss of generality one can assume that each element $u_i(t)$ of the control vector has a saturation limit of 1. In other words the saturation function can be defined as follows:

$$sat(u_i(t)) = \begin{cases} 1 & 1 \le u_i(t) \\ u_i(t) & -1 \le u_i(t) \le 1 \\ -1 & u_i(t) \le -1 \end{cases} \tag{5}$$

The proposed method is twofold, first the compensator is designed without considering any saturation limit, then a time varying scalar gain $0<\lambda(t)\le 1$ is added which modifies error and is adjusted via a supervisory loop (figure 2) to cope with saturation.

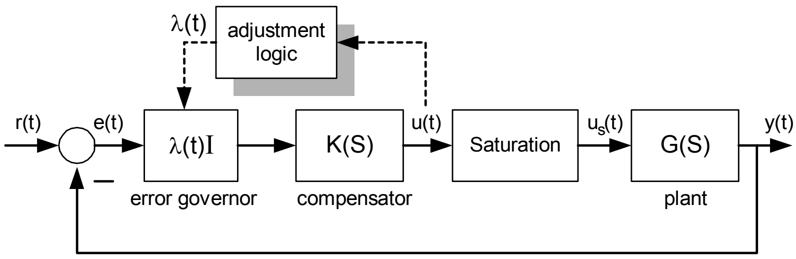

Figure 2: The closed loop system with error governor

Intuitively one can state the logic of adjustment as follows:

- If the system is to experience saturation make λ smaller,
- Otherwise increase λ up to one.

This logic decreases the bandwidth when the system is to experience saturation and in normal conditions the effect of error governor is diminished by making λ=1. This configuration reduces the amplitude of the control effort as is done by saturation itself but there are some important differences: 1) this is a dynamic compensator and not a hard nonlinearity as is the case with saturation; 2) this approach limits the control effort by affecting the controller states while saturation will limit the control effort independent of the controller states, in other word it acts in a closed loop but saturation acts open loop. It is difficult to implement this logic with a rigorous mathematical model and if done it will not be implementable. However with fuzzy logic this can be easily employed. To sense the value of nearness to saturation the absolute value of the amplitude of the control effort $|u(t)|$ is a good measure. To give a kind of prediction to the logic, $\dot{u}(t)$ is also taken into account. The above logic thus can be interpreted to the fuzzy notation as follows:

- If $|u(t)|$ is *NEAR* to one and $\dot{u}(t)$ is *POSITIVE* make λ *LESS* than one,
- When $|u(t)|$ is *OVER* one, make λ *SMALL* if $\dot{u}(t)$ is negative and *VERY SMALL* if $\dot{u}(t)$ is not negative,
- Otherwise make it *ONE* (see table 1).

Fuzzy sets are defined as shown in figures 3 to 5.

Table 1: Fuzzy Rules

$\dot{u}$ \ $\|u\|$	**Small**	**Near**	**Over**
Neg	One	One	S
Zero	One	One	VS
Pos	One	L	VS

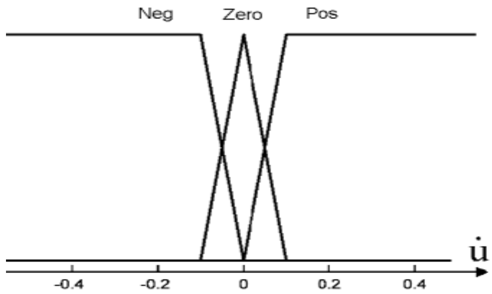

Figure 3: Fuzzy sets for $\dot{u}(t)$

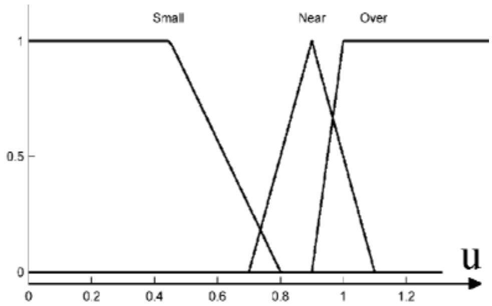

Figure 4: Fuzzy sets for u

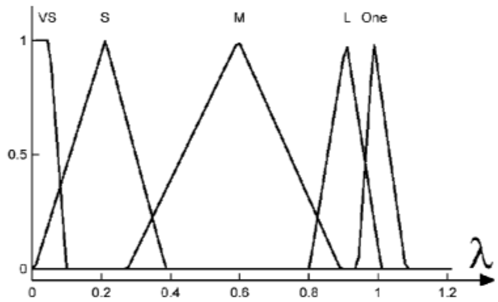

Figure 5: Fuzzy sets for λ

To use this strategy for the FJR some modifications should be made as follow:

a. The supervisor is used for the fast subsystem only which mainly causes the instability when limited by saturation.
b. In simulations where the desired reference input is a sinusoid and so is the control effort, use of $|u(t)|$ is meaningless and the amplitude of the sinusoid must be considered instead. Practically a low pass filter is used to estimate this amplitude.
c. The saturation limit is not 1 in the FJR configuration, so the control effort $u(t)$ must be attenuated by this factor before feeding to the supervisor.

The modified supervisory loop for the FJR is shown in figure 6. a filter is used to estimate $\dot{u}(t)$ from $u(t)$ so the only measurement is $u(t)$.

Simulation

Simulation conditions and measures

The effectiveness of the proposed method is verified through simulations. A single degree of freedom FJR is considered as shown in figure 7. The numerical values are selected as the benchmark problem in the literature [10, 14, 15] to be: *m=1, I=1, J=1, L=1, g=9.8, k=100*.

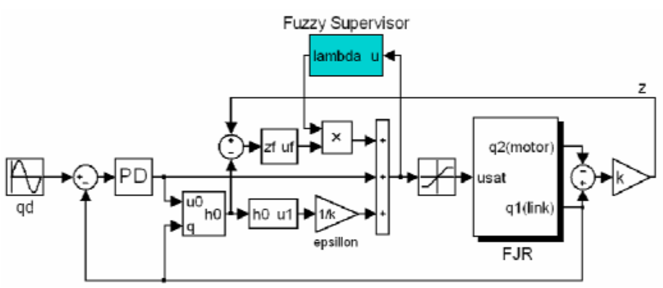

Figure 6: Fuzzy supervisor for the FJR

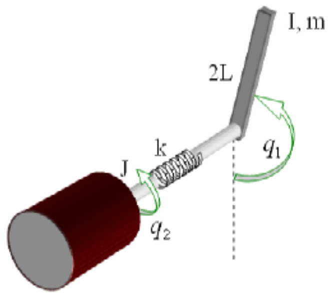

Figure 7: The single degree of freedom FJR

The reference input is selected to be $q_d = Sin(8t)$. This is the largest bandwidth desired for this benchmark in the literature. With this input the control effort at the steady state will have amplitude of about 80, so a saturation limit between 100 and 150 is reasonable. As the error has not a zero steady state value, to be accurate the, $\mathcal{L}_{2e}$ norm of the error which is the $\mathcal{L}_2$ norm of the truncated signal $e_\tau(t)$ is considered [16]:

$$e_\tau(t) = \begin{cases} e(t) & 0 < t < \tau \\ 0 & \tau < t \end{cases} \tag{6}$$

To have a quantitative measure of performance the following definition will be helpful:

Definition: a *minimum acceptable limit*, δ_{min} is defined as the saturation limit that preserves stability itself but a reduction of 5 percent in it will cause instability.

Simulation results

A. Original system. The desired output, $q_d(t)$ and the simulated output, $q(t)$ for the original system (without fuzzy supervisor) in the absence of saturation are shown in figure 8.

If saturation is added to the model, for the values of saturation limit that are not large enough instability will occur. The instable output for the saturation limit $\delta = 830$ is shown in figure 9.

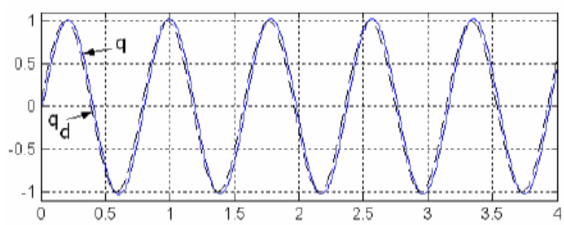

Figure 8: Tracking, no saturation, no supervision

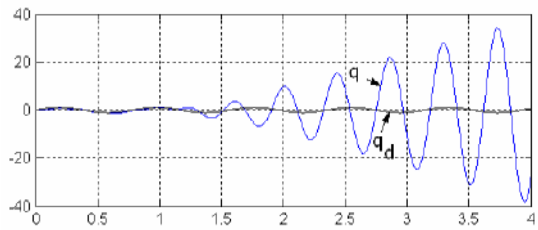

Figure 9: Instability due to saturation for $\delta = 830$

The minimum acceptable limit for this case is $\delta_{min} = 870$ (table 2). The error norms are shown in the upper shaded rows of table 3.

B. Supervised system. If the supervisor is added to the system the minimum acceptable limit will reduce to $\delta_{min} = 145$ (table 2) which is a reasonable value. The tracking graph for this case is shown in figure 10 with comparable axes as in figure 8.

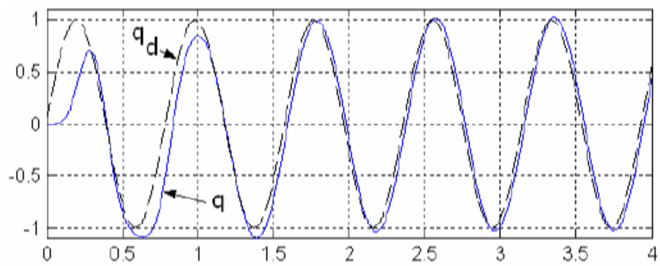

Figure 10: Tracking with δ = 830 in presence of supervisor

The value of λ for this case is shown in figure 11. Its value is near to zero during "take off" of the system and after decay of the transients it will reach to the value of one at time $t = 4$, omitting the supervisor effects from the system and returning to the wide bandwidth which has been designed.

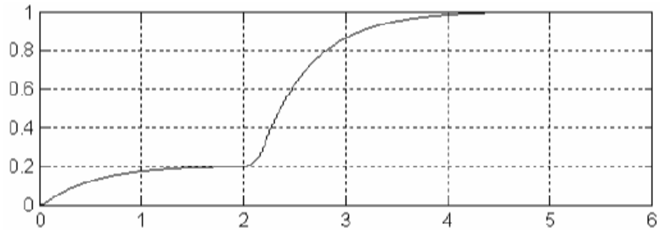

Figure 11: The value of λ with δ = 830

The error norms for this case (i.e. with supervisor) are shown in the lower rows of table 3. To have quantitative criteria to judge about these norms the norm of error during a period of the reference input for zero output may be useful. This value could theoretically found to be

$$\|e_\tau(t)\|_{\mathcal{L}2e}\Big|_{q(t)=0} = \|q_{d\tau}(t)\|_{\mathcal{L}2e} = 0.627, \quad \tau = \frac{2\pi}{\omega} = \frac{\pi}{4} \tag{7}$$

Allowing for the tracking graphs and taking into consideration the values of the norms one can deduce that the supervisory loop could reject the instability problem and to reduce the minimum acceptable limit while preserving a satisfactory tracking behaviour. In fact the main reason of instability which is limiting the fast (flexible) term in the control effort is attenuated by the supervisor in the beginning, in order to let the system to deal with inertias. On the other hand the fast term could not be fully omitted because ignoring flexibility will cause the controller to fail and may cause instability itself, so the supervisor will release the fast term when the system is settled down.

Table 2: minimum acceptable limit for two cases

	Original system	Supervised system
δ_{min}	870	145

table 3: error norms (shaded: original syst

δ	∞	10^3
$\|e_4(t)\|_{\mathcal{L}2e}$	0.210	0.302
	0.210	0.350
$\|e(t)\|_\infty$	0.15	0.55
	0.15	0.75

Conclusions

In this paper the problem of implementable controller design for flexible joint robots in presence of actuator saturation is considered in detail. The singularly perturbed model of the system is first introduced and the composite control strategy is explained briefly. It is shown that using a three term composite controller, good performance can be achieved in the absence of actuator saturation. In order to remedy the instability caused by actuator bounds, a supervisory loop is proposed. It is shown that a model free fuzzy supervisor makes it possible to reduce the minimum acceptable saturation limit, without great loss in performance. The used configuration will add a dynamic reduction in the control effort instead of the clipping action of the saturation. The supervisor will affect the signals *before* the controller so affecting the controller states dislike the saturation which will be placed *after* the controller

Moreover the method of composite control with PD terms for solid and flexible (fast) controls is used to skip over the offline computations and to omit the rate measurements. These all considerations have been enabled us to offer a practical controller for an FJR.

References

[1] Machida K., Nishida H., Akita K., "Precise telerobotic system for space experiment on ETS-VII", 1998

[2] Liu H., Meusel P., Butterfass J., Hirzinger G., "DLR's Multisensory articulated hand. Part II : The parallel torque/position control system", *IEEE Int. Conf. on Robotics and Automation*,1998

[3] Sweet L.M., Good M.C., "Re-definition of the robot motion control problems: Effects of plant dynamics, drive system constraints, and user requirements", *IEEE Int. Conf. on Decision and Control*,1984

[4] Cesareo G., Marino R., "On the controllability properties of elastic robots", *Int. Conf. Analysis and Optimization of Systems*,1984

[5] 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", 1990

[6] Ozgoli S., Taghirad H.D., "A survey on the control of flexible joint robots", *Iranian Conf. Electrical Eng.*, IRAN, 2004. (submitted to)

[7] Ozgoli S., "Position control for flexible joint robots in presence of actuator saturation", PhD thesis proposal, accepted 2002.

[8] Kapasouris P., Athans M., Stein G., "Design of feedback control systems for stable plants with saturating actuators", *IEEE Int. Conf. on Decision and Control*, 1988

[9] Ozgoli S., Taghirad H.D., "Fuzzy supervisory loop as a remedy for actuator saturation drawbacks", *16th Int. Conf. System Eng.*, UK, 2003.

[10] Spong M.W., "Modeling and Control of elastic joint robots", *Journal of Dynamic Systems, Measurement, and Control*,1987

[11] Spong M.W., Khorasani K., Kokotovic P.V., "An integral manifold approach to the feedback control of FJRs", *IEEE Journal of Robotics and Automation*, 1987

[12] Chow J.H., Kokotovic P.V., "Two-time-scale feedback design of a class of nonlinear systems", *IEEE Trans. on Automatic Control*, 1978

[13] Taghirad H.D., Khosravi M.A., "Stability Analysis and robust PID design for flexible joint robots", *Int. Symp. Robotics.*, 2002.

[14] Al Ashoor R.A., Khorasani K., Patel R.V., Al-Khalili A.J., "Adaptive Control of FJM", *IEEE Int. Conf. on Systems, Man and Cybernetics*,1984

[15] Amjadi F R., Khadem S.E., Khaloozadeh H., "Position and velocity control of a FJR manipulator via fuzzy ontroller based on singular perturbation analysis", *IEEE Int. Fuzzy Systems Conf.*,2001

[16] Khalil H., *Nonlinear Systems,* 2nd Ed., Section 6.1.