Designing Type-1 Fuzzy Logic Controllers via Fuzzy Lyapunov Synthesis for Nonsmooth Mechanical Systems: The Perturbed Case

Diseño de Controladores Difusos Tipo-1 a través de la Síntesis Difusa de Lyapunov para Sistemas Mecánicos No Suaves: El Caso Perturbado

Nohe Ramón Cazarez Castro[1], Luis Tupak Aguilar Bustos[2] and Oscar Castillo López[3]

[1]Facultad de Ciencias Químicas e Ingeniería, Universidad Autónoma de Baja California
Tijuana, México
nohe@ieee.org
[2]Centro de Investigación y Desarrollo de Tecnología Digital, Instituto Politécnico Nacional
Tijuana, México
luis.aguilar@ieee.org
[3]División de Estudios de Posgrado e Investigación, Instituto Tecnológico de Tijuana
Tijuana, México
ocastillo@hafsamx.org

Abstract. Fuzzy Lyapunov Synthesis is extended for the design of type-1 fuzzy logic controllers for an output regulation problem for a servomechanism with backlash. The problem in question is to design a feedback controller so as to obtain the closed-loop system in which all trajectories are bounded and the load of the driver is regulated to a desired position while also attenuating the influence of external disturbances. Provided the servomotor position is the only measurement available for feedback, the proposed extension is far from trivial because of nonminimum phase properties of the system. Performance issues of the fuzzy regulator constructed are illustrated in an experimental study..
Keywords: Fuzzy Control, Fuzzy Lyapunov Synthesis, Stability, Nonsmooth systems.

Resumen. La Síntesis Difusa de Lyapunov se extiende para el diseño de controladores difusos tipo-1 para un problema de regulación de salida de un servomecanismo con backlash. El problema en cuestión es el diseño de un controlador retroalimentado para obtener el sistema de lazo cerrado en el cual todas las trayectorias están acotadas y la carga del mecanismo se regula en una posición determinada a la vez que atenúa la influencia de perturbaciones externas. La posición del servomotor es la única medida disponible para retroalimentación, la propuesta está lejos de ser trivial debido a las propiedades de fase no mínima del sistema. El funcionamiento de los reguladores difusos construidos se muestran en un estudio experimental.
Palabras clave: Control Difuso, Síntesis Difusa de Lyapunov, Estabilidad, Sistemas no suaves.

1 Introduction

A major problem in control engineering is a robust feedback design that asymptotically stabilizes a plant while also attenuating the influence of parameter variations and external disturbances. In the last decade, this problem was heavily studied and considerable research efforts have resulted in the development of systematic design methodologies for nonlinear feedback systems. A survey of these methods, fundamental in this respect is given in [12].

The design of Fuzzy Logic Systems (FLSs) is a heavy task that FLSs practitioners face every time that they try to use Fuzzy Logic (FL) as a solution to some problem, the design of FLSs implies at least two stages: design of the rule-base and design of the Membership Functions (MFs).

There have been some publications in the design of Type-1 Fuzzy Logic Systems (T1FLS), for example [10] presents Genetic Algorithms (GA) as an optimization method for control parameters, they optimize parameters of the closed-loop system but not of the T1FLS. In [15] GAs are used to optimize all the parameters of a T1FLS. In [19] a hybridization of Neural Networks and GAs are presented to optimize a T1FLSs. A Hierarchical Genetic Algorithms is proposed in [2] to optimize rules and MFs parameters of a T1FLS.

In the present paper the output regulation problem is studied for an electrical actuator consisting of a motor part driven by a DC motor and a reducer part (load) operating under uncertainty conditions in the presence of nonlinear backlash effects and external disturbances. The objective is to drive the load to a desired position while providing the roundedness of the system motion and attenuating external disturbances. Because of practical requirements (see e.g., [14]), the motor's angular position is assumed to be the only information available for feedback.

This problem was first reported in [1], where the problem of controlling nonminimum phase systems was solved by using nonlinear H_∞ control, but the reported results do not provide robustness evidence. In [5], authors report a solution to the regulation problem using a T1FLS. In [6] and [8], authors report solutions using Type-2 Fuzzy Logic Systems Controllers, and making a genetic optimization of the membership function's parameters, but do not specify the criteria used in the optimization process and GA design. In [7], a comparison of the use of GAs to optimize Type-1 and Type-2 FLS Controllers is reported, but a method to achieve this optimization is not provided. In [9], is presented the designing of the Type-1 FLS following the Fuzzy Lyapunov Synthesis [18] to obtain a FLS for the output regulation of a servomechanism with backlash, but the reported results do not provide robustness evidence in the presence of external disturbances.

In this paper we extend the results from [9] by designing a Type-1 FLS (Fuzzy Logic Controller - FLC-) extending the Fuzzy Lyapunov Synthesis, a concept that is based on the Computing with Words [20][23] approach of the Lyapunov Synthesis [13], in order to provide robustness evidence in the presence of external disturbances. Additionally, this paper presents a new dynamical model of the case of study, adding a new term that represents the viscous friction present in the mechanism, and results showing the robustness of the designed controllers including noise in the experiments, we also present some measures that allow to make a comparison between the performance of the fuzzy controllers in the experimental results.

The contributions of this paper are as follows:
- We propose a systematic methodology to design Type-1 FLCs via the Fuzzy Lyapunov Synthesis.

- With the proposed methodology we obtain Type-1 FLCs, which due to the nature of designing method, are stable.
- We solve the output regulation problem for an electrical actuator operating under uncertainty conditions in the presence of nonlinear backlash effects and external disturbances.
- We show that the resulting FLSs are so robust that they can deal with the proposed problem.

The paper is organized as follows. The dynamic model of the nonminimum phase servomechanism with nonlinear backlash and the problem statement are presented in Sections 2 and 3, respectively. Section 4 addresses fuzzy sets and systems theory. The design of Fuzzy Logic Controllers using the Fuzzy Lyapunov Synthesis is presented in Section 5. The numerical simulations for the designed FLSs are presented in Section 6. Conclusions are presented in Section 7.

2 Dynamic model

The dynamic model of the angular position $q_i(t)$ of the DC motor and the $q_o(t)$ of the load are given according to

$$
\begin{aligned}
J_0 N^{-1}\ddot{q}_0 + f_0 N^{-1}\dot{q}_0 &= T + w_0, \\
J_i \ddot{q}_i + f_i \dot{q}_i + T &= \tau_m + \Gamma_c(\dot{q}_i) + w_i,
\end{aligned}
\tag{1}
$$

hereafter, J_0, f_0, $\ddot{q}_0$ and $\dot{q}_0$ are, respectively, the inertia of the load and the reducer, the viscous output friction, the output acceleration, and the output velocity. The inertia of the motor, the viscous motor friction, the motor acceleration, and the motor velocity are denoted by J_i, f_i, $\ddot{q}_i$, and $\dot{q}_i$, respectively. The input torque τ_m serves as a control action, and T stands for the transmitted torque. $\Gamma_c(\dot{q}_i)$ is the Coulomb friction torque which affects the motor dynamics. The external disturbances $w_i(t)$, $w_0(t)$ have been introduced into the driver equation (1) to account for destabilizing model discrepancies due to hard-to-model nonlinear phenomena, such as friction and backlash.

The transmitted torque T through a backlash with amplitude j is typically modeled by a dead-zone characteristic [p. 7, 22]:

$$
T(\Delta q) = \begin{cases} 0 & |\Delta q| \leq j \\ K\Delta q - Kj(\Delta q) & \text{otherwise} \end{cases},
\tag{2}
$$

with

$$\Delta q = q_i - N q_0, \qquad (3)$$

where K is the stiffness, and N is the reducer ratio. Such a model is depicted in Fig. 1. Provided the servomotor position $q_i(t)$ is the only available measurement on the system, the above model (1)-(3) appears to be non-minimum phase because along with the origin the unforced system possesses a multivalued set of equilibria (q_i, q_0) with $q_i = 0$ and $q_0 \in [-j, j]$.
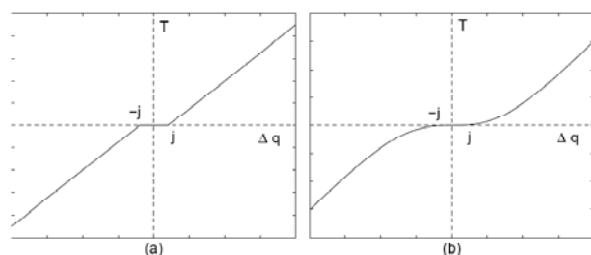

Fig. 1. Dead-zone model of backlash and its monotonic approximation

To avoid dealing with a non-minimum phase system, we replace the backlash model (2) with its monotonic approximation:

$$\mathrm{T} = \mathrm{K}\Delta q - K\eta(\Delta q), \qquad (4)$$

where

$$\eta = -2j \frac{1 - \exp\left\{-\frac{\Delta q}{j}\right\}}{1 + \exp\left\{-\frac{\Delta q}{j}\right\}}. \qquad (5)$$

The present backlash approximation is inspired from [21]. Coupled to the drive system (1) subject to motor position measurements, it is subsequently shown to continue a minimum phase approximation of the underlying servomotor, operating under uncertainties $w_i(t)$, $w_0(t)$ to be attenuated. As a matter of fact, these uncertainties involve discrepancies between the physical backlash model (2) and its approximation (4) and (5).

3 Problem Statement

To formally state the problem, let us introduce the state deviation vector $x = [x_1, x_2, x_3, x_4]^T$ with

$$x_1 = q_0 - q_d,$$
$$x_2 = \dot{q}_0,$$
$$x_3 = q_i - N q_d,$$
$$x_4 = \dot{q}_i,$$

where x_1 is the load position error, x_2 is the load velocity, x_3 is the motor position deviation from its nominal value, and x_4 is the motor velocity. The nominal motor position $N q_d$ has been pre-specified in such a way to guarantee that $\Delta q = \Delta x$, where $\Delta x = x_3 - N x_1$.

Then, system (1)-(5), represented in terms of the deviation vector x, takes the form

$$
\begin{aligned}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= J_0^{-1}[KN x_3 - KN^2 x_1 - f_0 x_2 + KN\eta(\Delta q) + w_o], \\
\dot{x}_3 &= x_4, \\
\dot{x}_4 &= J_i^{-1}[\tau_m + KN x_1 - K x_3 - f_i x_4 + K\eta(\Delta q) + \Gamma_c(\dot{q}_i) + w_i].
\end{aligned}
\qquad (6)
$$

The zero dynamics

$$
\begin{aligned}
\dot{x}_1 &= x_2, \\
\dot{x}_2 &= J_0^{-1}[-KN^2 x_1 - f_0 x_2 + KN\eta(-N x_1)],
\end{aligned}
\qquad (7)
$$

of the undisturbed version of system (6) with respect to the output

$$\mathrm{y} = \mathrm{x}_3, \qquad (8)$$

is formally obtained ([11] for details) by specifying the control law that maintains the output identically to zero.

The objective of the Fuzzy Control output regulation of the nonlinear driver system (1) with backlash (4) and (5), is thus to design a Fuzzy Controller so as to obtain the closed-loop system in which all these trajectories are bounded and the output $q_0(t)$ asymptotically decays to a desired position q_d as $t \to \infty$ while also attenuating the influence of the external disturbances $w_i(t)$ and $w_0(t)$.

4 Type-1 Fuzzy Sets and Systems

A Type-1 Fuzzy Set (T1FS), denoted A is characterized by a Type-1 membership function (T1MF) $\mu_A(z)$ [3], where $z \in Z$, and Z is the domain of definition of the variable, i.e,

$$A = \{(z, \mu(z)) | \forall z \in Z\}, \qquad (9)$$

where $\mu(z)$ is called a Type-1 **membership function** of the T1FS A. The T1MF maps each element of Z to a membership grade (or membership value) between 0 and 1.

Type-1 Fuzzy Logic Systems (T1FLS) - also called Type-1 Fuzzy Inference Systems (T1FIS)-, are both, intuitive and numerical systems that map crisp inputs into a crisp output. Every T1FIS is associated with a set of rules with meaningful linguistic interpretations, such as:

$$R^l : \text{IF } y \text{ is } A_1^l \text{ AND } \dot{y} \text{ is } A_2^l \text{ THEN } u \text{ is } B_1^l, \quad (10)$$

which can be obtained either from numerical data, or from experts familiar with the problem at hand. In particular (10) is in the form of Mamdami fuzzy rules [16]—[17]. Based on this kind of statements, actions are combined with rules in an antecedent/consequent format, and then aggregated according to approximate reasoning theory to produce a nonlinear mapping from input space $U = U_1 \times U_2 \times \cdots \times U_n$ to output space W, where $A_k^l \subset U_k$, $k = 1, 2, \ldots, n$, and the output linguistic variable is denoted by τ_m.

A T1FIS consists of four basic elements (see Fig. 2: the **Type-1 fuzzifier**, the **Type-1 fuzzy rule-base**, the **Type-1 inference engine**, and the **Type-1 defuzzifier**. The **Type-1 fuzzy rule-base** is a collection of rules in the form of (10), which are combined in the **Type-1 inference engine**, to produce a fuzzy output. The **Type-1 fuzzifier** maps the crisp input into a T1FS, which are subsequently used as inputs to the **Type-1 inference engine**, whereas the **Type-1 defuzzifier** maps the T1FSs produced by the **Type-1 inference engine** into crisp numbers.
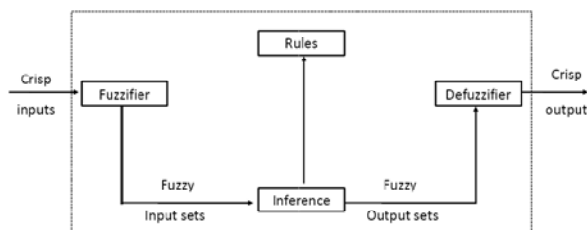

Fig. 2. Type-1 Fuzzy Inference System

In this paper, to get the crisp output of Fig. 2, we compute a Centroid of Area (COA) [3] as a *Type-1 defuzzifier*. The COA is defined as follows:

$$\tau_m = u_{COA} = \frac{\int_u \mu_A(u) u \, du}{\int_u \mu_A(u) \, du}, \qquad (11)$$

where $\mu_A(u)$ is the aggregated output of the T1MF. This is the most widely adopted defuzzification strategy, which is reminiscent of the calculation of expected values in probability distributions.

5 Design of the Fuzzy Logic Controllers

To apply the Fuzzy Lyapunov Synthesis, we assume the following:

- The system may have really two degrees of freedom referred to as x_1 and x_2, respectively. Hence by (6), $\dot{x}_1 = x_2$.
- The states x_1 and x_2 are the only measurable variables.
- The exact equations (1)-(5) are not necessarily known.
- The angular acceleration $\dot{x}_2$ is proportional to τ_m, that is, when τ_m increases (decreases) $\dot{x}_2$ increases (decreases).
- The initial conditions $x(0) = (x_1(0), x_2(0))^T$ belong to the set $\aleph = \{x \in^2 : \|x - x^*\| \le \varepsilon\}$ where x^* the equilibrium point is.

The *control objective* is to design the rule-base as a fuzzy controller $\tau_m = \tau_m(x_1, x_2)$ to stabilize the system (1)-(5).

Theorem 1 that follows establishes conditions that help in the design of the fuzzy controller to ensure asymptotic stability. The proof can be found in [13].

Theorem 1 (Asymptotic stability [13]) *Consider the nonlinear system (1)-(5) with an equilibrium point at the origin, i.e., f(0)=(0), and let $x \in \aleph$, then the origin is asymptotically stable if there exists a scalar Lyapunov function $V(x)$ with continuous partial derivatives such that*

- $V(x)$ *is positive definite*
- $\dot{V}(x)$ *is negative definite*

The fuzzy controller design proceeds as follows. Let us introduce the Lyapunov function candidate

$$V(x_1, x_2) = \tfrac{1}{2} \left(x_1^2 + x_2^2 \right), \qquad (12)$$

which is positive-definite and radially unbounded function. The time derivative of $V(x_1, x_2)$ results in:

$$(\mathrm{x}_1, x_2) = x_1\dot{x}_1 + x_2\dot{x}_2 = x_1 x_2 + x_2\dot{x}_2. \qquad (13)$$

To guarantee stability of the equilibrium point $(x_1^*, x_2^*)^T = (0,0)^T$ we require that:

$$\mathrm{x}_1 x_2 + x_2\dot{x}_2 \leq 0. \qquad (14)$$

We can now derive sufficient conditions so that inequality (14) holds: If x_1 and x_2 have opposite signs, then $x_1 x_2 < 0$ and (14) will hold if $\dot{x}_2 = 0$; if x_1 and x_2 are both positive, then (14) will hold if $\dot{x}_2 < -x_1$; if x_1 and x_2 are both negative, then (14) will hold if $\dot{x}_2 > -x_1$.

We can translate these conditions into the following fuzzy rules:

- If x_1 is *positive* and x_2 is *positive* then $\dot{x}_2$ must be *negative big*.

- If x_1 is *negative* and x_2 is *negative* then $\dot{x}_2$ must be *positive big*.

- If x_1 is *positive* and x_2 is *negative* then $\dot{x}_2$ must be *zero*.

- If x_1 is *negative* and x_2 is *positive* then $\dot{x}_2$ must be *zero*.

However, using our knowledge that $\dot{x}_2$ is proportional to u, we can replace each $\dot{x}_2$ with u to obtain the following fuzzy rule-base for the stabilizing controller:

- If x_1 is *positive* and x_2 is *positive* then u must be *negative big*.

- If x_1 is *negative* and x_2 is *negative* then u must be *positive big*.

- If x_1 is *positive* and x_2 is *negative* then u must be *zero*.

- If x_1 is *negative* and x_2 is *positive* then u must be *zero*.

This fuzzy rule-base can be represented as in Table 1.

It is interesting to note that the fuzzy partitions for x_1, x_2, and u follow elegantly from expression (13). Because $\dot{V} = x_2 (x_1 + \dot{x}_2)$, and since we require that $\dot{V}$ be negative, it is natural to examine the signs of x_1 and x_2; hence, the obvious fuzzy partition is *positive*, *negative*. The partition for $\dot{x}_2$, namely *negative big*, *zero*, *positive big* is obtained similarly when we plug the linguistic values *positive*, *negative* for x_1 and x_2 in (13).

To ensure that $\dot{x}_2 < -x_1 \ (\dot{x}_2 > -x_1)$ is satisfied even though we do not know x_1's exact magnitude, only that it is *positive* (*negative*), we must set $\dot{x}_2$ to *negative big* (*positive big*). Obviously, it is also possible to start with a given, pre-defined, partition for the variables and then plug each value in the expression for $\dot{V}$ to find the rules. Nevertheless, regardless of what comes first, we see that fuzzy Lyapunov synthesis transforms classical Lyapunov synthesis from the world of exact mathematical quantities to the world of computing with words [23], [20].

To complete the controller's design, we must model the linguistic terms in the rule-base using fuzzy membership functions and determine an inference method. Following [4], we characterize the linguistic terms *positive*, *negative*, *negative big*, *zero* and *positive big*. The T1MFs are depicted in Fig. 3. To this end, we had systematically designed a FLC following the Lyapunov stability criterion.

Table 1. IF-THEN rules

No.	Error	Change of Error	Control
1	positive	positive	negative big
2	negative	negative	positive big
3	positive	negative	zero
4	negative	positive	zero

6 Results

To perform simulations we use the dynamical model (1)-(5) of the experimental testbed installed in the Robotics \& Control Laboratory of CITEDI-IPN (see Fig. 4, which involves a DC motor linked to a mechanical load through an imperfect contact gear train [1]. The parameters of the dynamical model (1)-(5) are given in Table 2, while $N = 3$, $j = 0.2$ [rad], $K = 5$[N-m/rad], and $\Gamma_c(\dot{q}_i) = 0.2$. These parameters are taken from the experimental testbed.
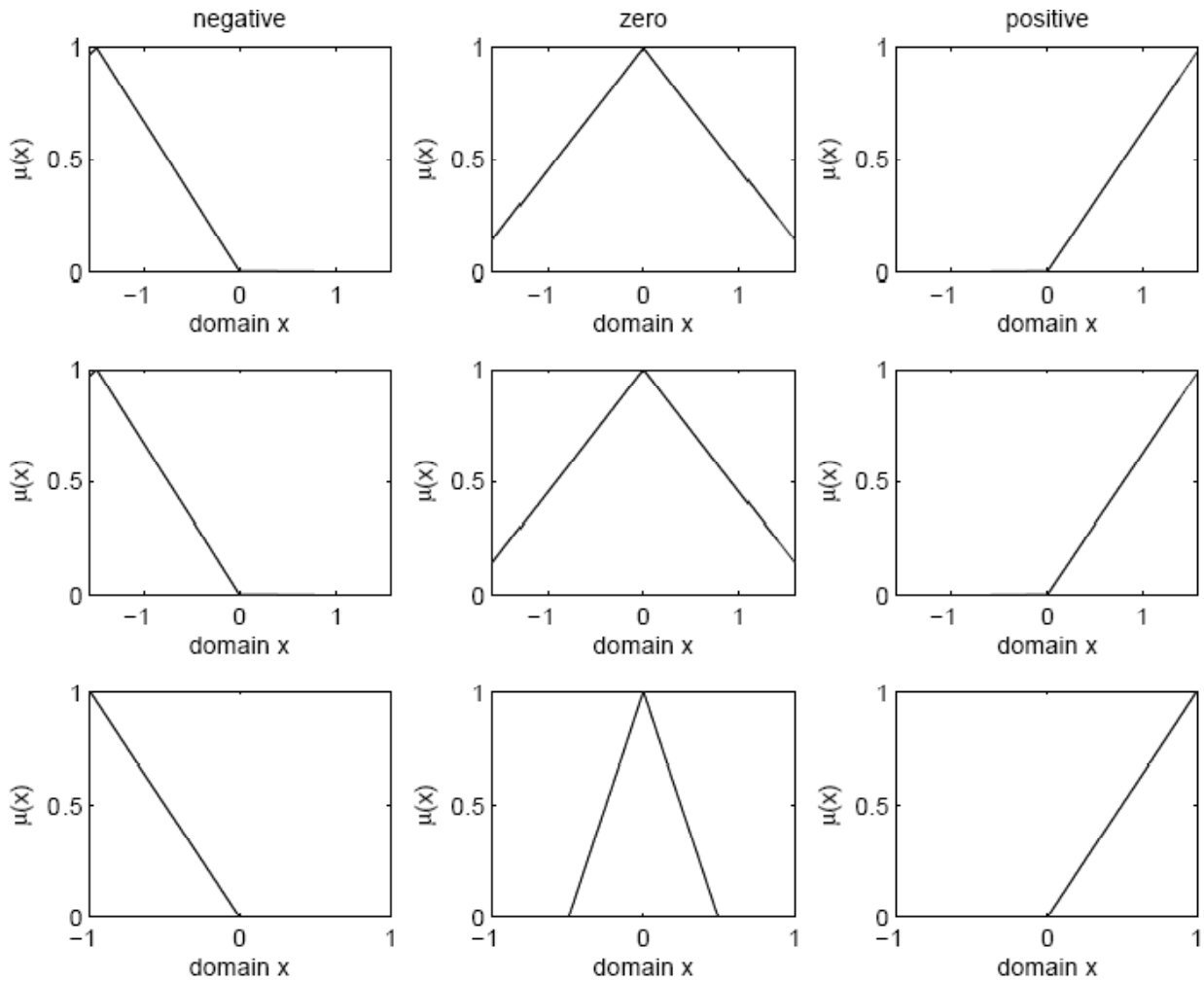
Fig. 3. Set of type-1 membership functions

Table 2. Nominal parameters

Description	Notation	Value	Units
Motor inertia	J_i	2.8×10^{-6}	Kg-m^2
Load inertia	J_o	1.07	Kg-m^2
Motor viscous friction	f_i	7.6×10^{-7}	N-m-s/rad
Load viscous friction	f_o	1.73	N-m-s/rad

6.1 Noise free

Performing a simulation of the closed-loop system (1)-(4) with the Type-1 FLC designed in Section 5 and $w_0 = w_i = 0$, and we have the following results: the control surface of Fig. 5 and we obtain the system's response of Fig. 6, showing that the load reaches the desired position, although we only have feedback from the motor position, x_1 and x_2 trajectories are in Fig. 7, in which can seen that $q_0 \to q_d$ while $x_0 \to 0$. In Fig. 8 the trajectories for (12) and (13) are depicted, satisfying Theorem 1.
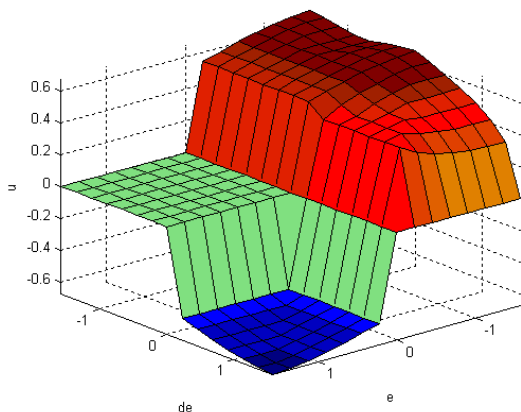
Fig. 4. Experimental testbed
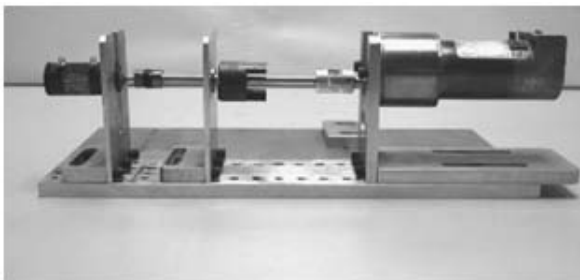
Fig. 7. x_1 and x_2 trajectories for the T1FLC
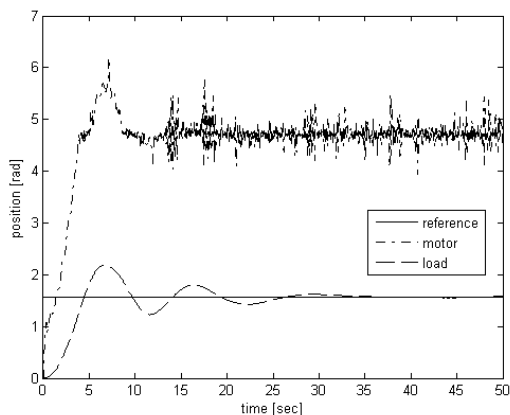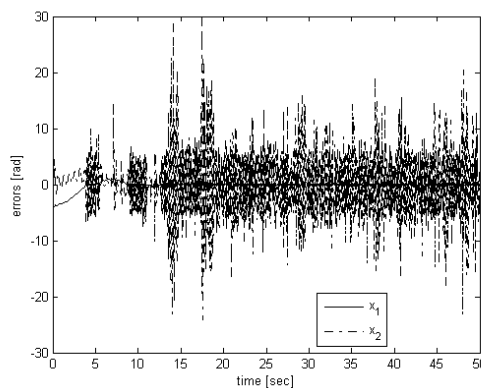

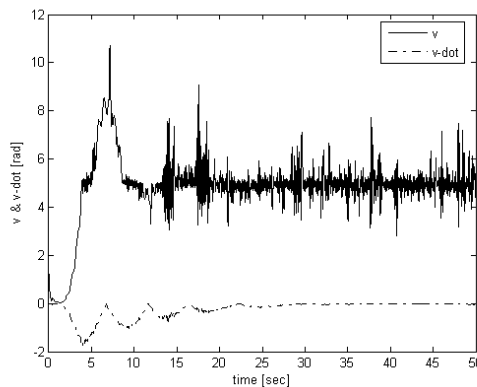**Fig. 5.** Control surface for the T1FLC

Fig. 8. V and $\dot{V}$ trajectories for the T1FLC

6.2 Random Noise

In order to verify the robustness of the proposed FLC, we perform a simulation of the closed-loop system (1)-(4) with the Type-1 FLC designed in Section 5 and $w_0 = w_i = random()$ (in Fig. 9 is depicted de noise signal), and we have the following results: system's response of Fig. 10 showing that the load reaches the desired position although we only have feedback from the motor position, x_1 and x_2 trajectories are in Fig. 11, in which can seen that $q_0 \to q_d$ while $x_0 \to 0$. In Fig. 12 the trajectories for (12) and (13) are depicted satisfying Theorem 1.
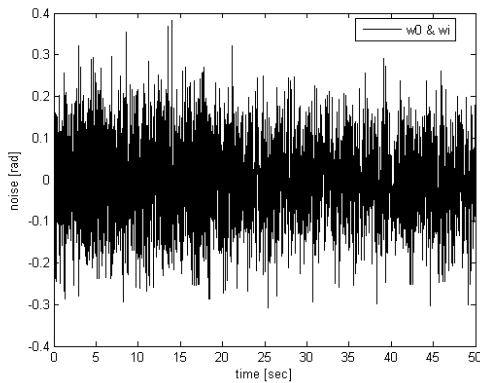

Fig. 6. System's response for the T1FLC
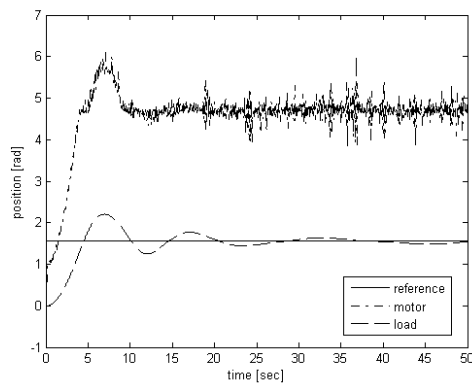
Fig. 9. $w_0 = w_i = random()$ signal
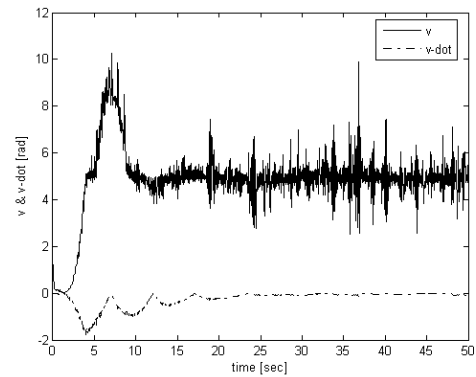
Fig. 10. System's response for the T1FLC and
$w_0 = w_i = random()$

Fig. 11. x_1 and x_2 trajectories for the T1FLC and
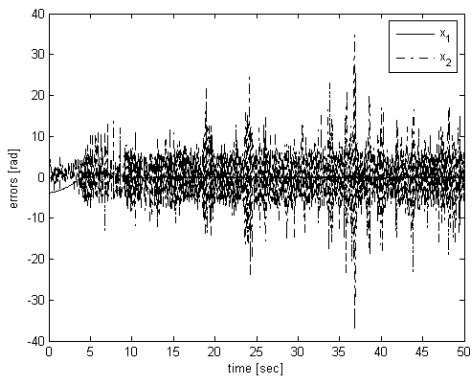$w_0 = w_i = random()$

Fig. 12. V and $\dot{V}$ trajectories for the T1FLC and
$w_0 = w_i = random()$

6.3 Sinusoidal Noise

Again, in order to verify the robustness of the proposed FLC, we perform a simulation of the closed-loop system (1)-(4) with the Type-1 FLC designed in Section 5 and $w_0 = w_i = \sin(\omega t)$ with amplitude of 0.1 [rad] and frecuency of 10 (in Fig. 13 is depicted de noise signal), and we have the following results: system's response of Fig. 14 showing that the load reaches the desired position, although we only have feedback from the motor position, x_1 and x_2 trajectories are in Fig. 15, in which can seen that $q_0 \to q_d$ while $x_0 \to 0$. In Fig. 16 the trajectories for (12) and (13) are depicted, satisfying Theorem 1.

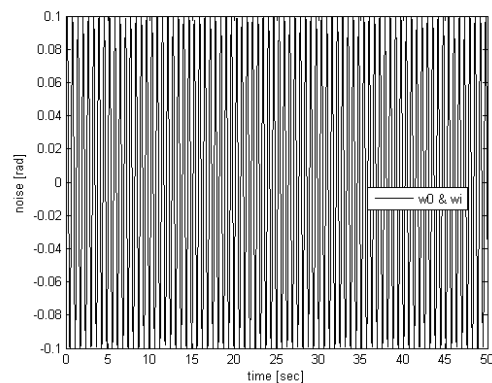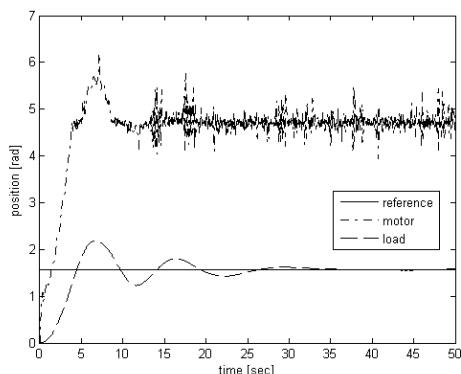**Fig. 13.** $w_0 = w_i = \sin(\omega t)$ signal

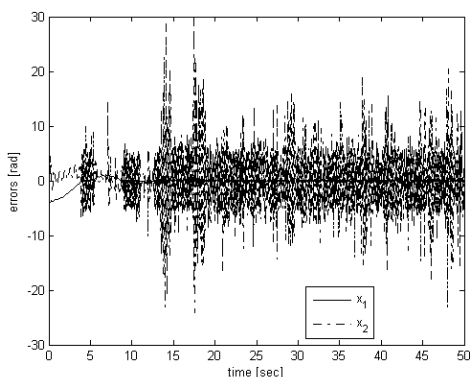**Fig. 14.** System's response for the T1FLC and
$$w_0 = \sin(\omega t)$$

Fig. 15. x_1 and x_2 trajectories for the T1FLC and
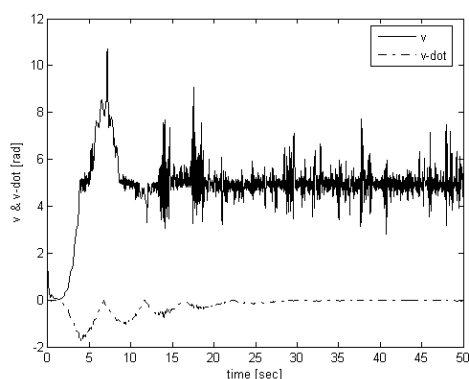$$w_0 = w_i = \sin(\omega t)$$

Fig. 16. V and $\dot{V}$ trajectories for the T1FLC and
$$w_0 = w_i = \sin(\omega t)$$

6.4 Comparison

The three experiments (noise free, with random noise and sinusoidal noise) were performed in a satisfactory fashion; the load was regulated in the set point in all the three cases. Now Table 3 concentrates some measures that can help us make a comparison between them, and as can be seen, the performance of the three experiments are very close in most measurements, but the settling time increases with both kind of noise.

Table 3. Comparison for the three experiments

Measurement	*Noise Free*	*Random Noise*	*Sinusoidal Noise*
Settling time	13.500	18.000	17.600
Overshoot	2.200	2.200	2.185
ISE	4.7395×10^4	4.3779×10^4	3.9373×10^4
IAE	1.3413×10^4	1.3679×10^4	1.2425×10^4
ITSE	8.5851×10^5	9.5549×10^5	9.5377×10^5
ITAE	2.6025×10^5	3.0120×10^5	3.0164×10^5

7 Conclusions

The main goal of this paper was to propose a systematic methodology to design T1FLCs to solve the output regulation problem of a servomechanism with nonlinear backlash.

The proposed design strategy results in a controller that guarantees that the load reaches the desired position q_d.

The regulation problem was solved as was predicted; this affirmation is supported with simulations where the T1FLC designed by following the Fuzzy Lyapunov Synthesis achieve the solution to the regulation problem.

Moreover, the results show that the designed fuzzy control systems are capable of dealing with uncertainties (disturbances) like noise and viscous friction added to the system.

References

1. **Aguilar, L.T., Orlov, Y., Cadiou, J.C. & Merzouki, R. (2007).** Nonlinear H_∞-output regulation of a nonminimum phase servomechanism with backlash. *Journal of Dynamic Systems, Measurement and Control,* 129(4), 544-549.

2. **Castillo, 0., Lozano, A. & Melin, P. (2004).** Hierarchical genetic algorithms for fuzzy system optimization in intelligent control. *IEEE Annual Meeting of the National Association of Fuzzy Information,* Banff, Canada, 292-297.

3. **Castillo, O. & Melin, P. (2008).** *Type-2 Fuzzy Logic: Theory and Applications.* New York: Springer-Verlag.

4. **Castillo, O., Aguilar, L.T., Cazarez, N. & Cardenas, S. (2008).** Systematic design of a stable type-2 fuzzy logic controller. *Journal of Applied Soft Computing,* 8(3), 1274-1279.

5. **Cazarez-Castro, N. R., Aguilar, L.T. , Castillo, O. & Cardenas, S. (2008).** Fuzzy Control for Output Regulation of a Servomechanism with Backlash. In Castillo O., Melin, P., Kacprzyk J., Pedrycz W. (Eds.), *Soft Computing for Hybrid Intelligent Systems* (19-28). Berlin: Springer-Verlag.

6. **Cazarez-Castro, N.R., Aguilar, L.T. & Castillo, O. (2008).** Hybrid Genetic-Fuzzy Optimization of a Type-2 Fuzzy Logic Controller. *Eighth International Conference on Hybrid Intelligent Systems,* Barcelona, España, 216-221.

7. **Cazarez-Castro, N.R., Aguilar, L.T., Castillo, O. & Rodriguez, A. (2008).** Optimizing Type-1 and Type-2 Fuzzy Logic Systems with Genetic Algorithms. *Research in Computing Science,* 39, 131-153.

8. **Cazarez-Castro, N.R., Aguilar, L.T. & Castillo, O. (2008).** Genetic optimization of a type-2 fuzzy controller for output regulation of a servomechanism with backlash. *5th International Conference on Electrical Engineering, Computing Science and Automatic Control,* Ciudad de Mexico, Mexico, 268-273.

9. **Cazarez-Castro, N.R., Aguilar, L.T. & Castillo, O. (2009).** Designing type-1 fuzzy logic controllers via fuzzy Lyapunov synthesis for nonsmooth mechanical systems. *Congreso Anual 2009 de la Asociacion de Mexico de Control Automatico,* Zacatecas, Mexico, cd-rom.

10. **Grefenstette, J.J. (1986).** Optimization of control parameters for genetic algorithms. *IEEE Transactions on Systems, Man, and Cybernetics,* 16(1), 122-128.

11. **Isidori, A. (1995).** *Nonlinear Control Systems.* New York: Springer-Verlag.

12. **Isidori, A. (2000).** A tool for semi-global stabilization of uncertain non-minimum-phase nonlinear systems via output feedback. *IEEE Transactions on Automatic Control,* 45(10), 1817-1827.

13. **Khalil, H. K. (2002).** *Nonlinear Systems.* New Jersey: Prentice Hall.

14. **Lagerberg, A. & Egardt, B. (2003).** Estimation of backlash with application to automotive powertrains. *42nd Conference on Decision and Control, 5,* Maui, USA, 4521-4526.

15. **Lee, M.A. & Takagi, H. (1993).** Integrating design stage of fuzzy systems using genetic algorithms. *Second IEEE International Conference On Fuzzy Systems,* San Francisco, USA, 612-617.

16. **Mamdani, E.H. (1976).** Advances in the linguistic synthesis of fuzzy controllers. *International Journal of Man- Machine Studies,* 8(6), 669-678.

17. **Mamdani, E.H. & Assilian, S. (1975).** An experiment in linguistic synthesis with fuzzy logic controller. *International Journal of Man-Machine Studies,* 7(1), 1-13.

18. **Margaliot, M. & Langholz, G. (1998).** Adaptive fuzzy controller design via fuzzy Lyapunov synthesis. *The 1998 IEEE International Conference on Fuzzy Systems,* 1, Archorage, AK, USA, 354-359.

19. **Melin, P. & Castillo, O. (2001).** Intelligent control of complex electrochemical systems with a neuro-fuzzy-genetic approach. *IEEE Transactions on Industrial Electronics.,* 48(5), 951-955.

20. **Mendel, J.M. (2007).** Computing with words: Zadeh, Turing, Popper and Occam. *IEEE Computational Intelligence Magazine,* 2(4), 10-17.

21. **Merzouki, R., Cadiou, J.C. & M'Sirdi, N.K. (2004).** Compensation of friction and backlash effects in an electrical actuator. *Journal of System And Control Engineering,* 218(2), 75-84.

22. **Nordin, M. P., Bodin, P. & Gutman, P. (2001).** New Models and Identification Methods for Backlash and Gear Play. In Tao G., Lewis F.L. (Eds.), *Adaptive Control of Nonsmooth Dynamic Systems* (1-30). Berlin: Springer-Verlag.

23. **Zadeh, L.A. (1996).** Fuzzy logic = computing with words. *IEEE Transactions on Fuzzy Systems,* 4(2), 103-111.

Nohe Ramón Cazarez Castro

Received the B.Sc.&Eng. in Computer Systems in 2002, and the M.Sc. in Computer Science in 2005, both from Tijuana Institute of Technology (Instituto Tecnológico de Tijuana), Tijuana, Mexico; he is currently working toward the PhD/DSc/DEng degree at Baja California Autonomous University (Universidad Autónoma de Baja California), Tijuana, Mexico. Has received grants from CONACYT (Mexican - National Council of Science and Technology) and SEP (Mexican - Secretary of Public Education) for studies and research. Since 1995 has been with some Universities and Software Consulting Companies, actually he is professor at Baja California Autonomous University. He has 30+ publications in national and international high impact journals, book chapters and conferences. Nohé's research interest centers in Computational Intelligence as applied to Autonomous Control and Robotics systems, and nonlinear control; main interest is in Type-2 Fuzzy Logic and Genetic Algorithms. He is student member of IEEE, IEEE Computational Intelligence Society, Hispanic-American Fuzzy System Association, and member of the International Association of Engineers (AIENG), AIENG Artificial

Intelligence Society and Mexican Association of Numeric's Methods Applied to Engineering, Mexican Society of Computing Science, and Young Researches Committee of the World Federation of Soft Computing.

Luis Tupak Aguilar Bustos

Received his Industrial Electronics Engineer diploma from Instituto Tecnologico de Tijuana, in 1994. He received his M. Sc. degree in Digital Systems from Digital Technology Research and Development Center (CITEDI-IPN), Tijuana, Mexico and his Ph.D. degree in Automatic Control from CICESE, Ensenada, Mexico, in 1998 and 2003, respectively. He is currently a full-time professor at the Instituto Politecnico Nacional from 2004. His research interest include variable structure systems, nonlinear H-infinity control, and control of underactuated systems and mechanical systems.

Oscar Castillo López

Holds the Doctor in Science degree (Doctor Habilitatus) in Computer Science from the Polish Academy of Sciences (with the Dissertation "Soft Computing and Fractal Theory for Intelligent Manufacturing"). He is a Professor of Computer Science in the Graduate Division, Tijuana Institute of Technology, Tijuana, Mexico. In addition, he is serving as Research Director of Computer Science and head of the research group on fuzzy logic and genetic algorithms. Currently, he is President of HAFSA (Hispanic American Fuzzy Systems Association) and Vice-President of IFSA (International Fuzzy Systems Association) in charge of publicity. Prof. Castillo is also Vice-Chair of the Mexican Chapter of the Computational Intelligence Society (IEEE). Prof. Castillo is also General Chair of the IFSA 2007 World Congress to be held in Cancun, Mexico. He also belongs to the Technical Committee on Fuzzy Systems of IEEE and to the Task Force on "Extensions to Type-1 Fuzzy Systems". He is also a member of NAFIPS, IFSA and IEEE. He belongs to the Mexican Research System. His research interests are in Type-2 Fuzzy Logic, Intuitionistic Fuzzy Logic, Fuzzy Control, Neuro-Fuzzy and Genetic-Fuzzy hybrid approaches. He has published over 60 journal papers, 5 authored books, 10 edited books, and 160 papers in conference proceedings. He has

been Guest Editor of several successful Special Issues in the past, like "Soft Computing for Control of Non-Linear Dynamical Systems" in the Journal of Applied Soft Computing, 2003 (Elsevier), "Hybrid Intelligent Systems" in the Journal of Non-Linear Studies, 2004 (I&S Publishers), and "Soft Computing for Modeling, Simulation, and "Control of Non-Linear Dynamical Systems" in the Journal of Intelligent Systems, 2005 (Wiley).