Multi-level Fuzzy-QFT Control of Conjugated Polymer Actuators

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Abstract

Conjugated polymer actuators can be employed to achieve micro and nano scale precision, and have wide range of applications including biomimetic robots and biomedical devices. In comparison to robotic joints, they do not have friction or backlash, but on the other hand, they have complicated electro-chemo-mechanical dynamics which makes modeling and control of the actuator really difficult. Besides the positive characteristics of these actuators, they have some disadvantages such as creep, hysteresis, highly uncertain and time-varying dynamic. This paper consists of two major parts. In the first part the Takagi–Sugeno (T–S) Fuzzy model is used to represent the uncertain dynamic of the actuator. The resulted Fuzzy model will be validated using existing experimental data. In the second part a multi-level controlling approach will be used to control the highly uncertain dynamic of conjugated polymer actuators. The first-level controller is a fuzzy controller and the second-level controller is a QFT controller. The fuzzy controller is designed to perform the main control action, while the QFT controller is used as a safeguard. The obtained results show that the designed controller can achieve good performance despite the existence of uncertain actuator dynamics.

1 Introduction

There is an increasing request for new generation of actuators which can be used in devices such as artificial organs, micro robots, human-like robots, and medical applications. Numerous researches have been done on developing new actuators such as shape memory alloys, piezoelectric actuators, magnetostrictive actuators, contractile polymer actuators, and electrostatic actuators [1], [2]. Comparison of these actuators indicates that Conjugated polymer actuators have superior characteristic over others [2,3]. The main process which is responsible for volumetric change and the resulted actuation ability of the conjugated polymer actuators is Reduction/Oxidation (RedOx). Thus based on different fabrication form, different configuration of the actuators can be obtained namely: linear extenders, bilayer benders, and trilayer benders [3-6]. By applying a voltage to the actuator, the polypyrrole (PPy) layer on the anode side is oxidized while that on the cathode side is reduced. Ions can transfer inside the Conjugated Polymer Actuators based on two main mechanisms namely diffusion and drift [7]. Since 2000 the Diffusive-Elastic-Metal model (DEM) remains to be the main model which could describe the actuation process in conjugated polymer actuators [7]. Several assumptions are needed to achieve the DEM model such as: 1) the electrical and mechanical parameters of the model are time invariant, 2) there is no coupling between the mechanical and electrical model, 3) the charge to strain ratio is linear and unidirectional, 4) there is no degradation in electrical or mechanical model, 5) the actuator is isothermal. On the other hand the dynamic of actuator is highly uncertain, and both electrical and mechanical degradation is inevitable during the actuator's lifecycle. Also continuum structure of DEM model is not suitable from control perspective. Reticulated Diffusion Model (RD) is proposed by T. A. Bowers in 2002 [8]. This model uses a reticulated network of linear circuit elements. The main advantage of RD over DEM model is that it can be represented in state space format and is suitable for linear system analysis techniques, but still it can not take into account system uncertainties based on its LTI structure. In our previous work, we used the Golubev Method [9] to build a suitable model for control of the actuator [3]. By taking into account the effects on uncertainties such as variation of the resistance and diffusion coefficient in the modeling, we replaced the dynamic of actuator with a family of third order LTI systems. However, we did not consider the interaction of these linear systems. This is the starting point in the present paper. In order to solve this problem, in this paper, the authors propose a Takagi–Sugeno Fuzzy model which can define the relation between local linear systems, and therefore predict the actuator's behavior under variation of the actuator's parameter. Application of PID controller for a polypyrrole actuator based on a first order model is presented in [10]. PID and adaptive control approaches based on a first order empirical model is demonstrated in [8]. In our previous works we used Robust Control QFT, and parallel distributed compensation (PDC) for controlling of a polypyrrole actuator based on a third order model [3,11]. In this paper we use a multi-level Fuzzy-QFT controller. Thus the reminder of the paper is structured as follows:

1) First the classical model of the actuator will be briefly reviewed. 2) The experimental data will be presented [9]. 3) Suitable T–S fuzzy model which can take into account variation of the actuator's parameter will be obtained. 4)

Finally a multi-level Fuzzy-QFT controller will be designed.

2 Electro-chemo-mechanical modelling

The electro-chemo-mechanical model is comprised of two parts, namely electrochemical model and electromechanical model.

2.1 Electrochemical Modelling

The electrochemical model relates the input voltage and chemical RedOx reaction inside the PPy actuators. Figure 1 depicts the electrical admittance model. Based on the Diffusive-Elastic-Metal model, transportation of ions within the polymer is only caused by diffusion [7]. According to Figure 1 and the Kirchhoff's voltage law one has:

$$I(s) = I_c(s) + I_D(s) \quad (1)$$

$$V(s) = I(s).R + \frac{1}{s.C} I_C(s) \quad (2)$$

Where Z_D is the diffusion impedance, C denotes the double-layer capacitance, and R is the electrolyte and contact resistance. Next based on Figure 2 and the Fick's law of diffusion, diffusion current is:

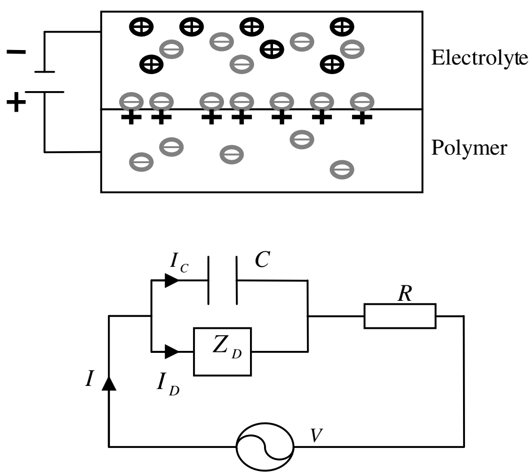

Figure 1 Description of diffusion and double layer charging and its equivalent electrical circuit.

$$i_D(t) = -F.A.D.\left.\frac{\partial c(x,t)}{\partial x}\right|_{x=0} \quad (3)$$

Where A is the surface area of the polymer, F is the Faraday constant, D is the diffusion coefficient, h is the thickness of the PPy layer, and c is the concentration ions. The current of double-layer capacitance is

$$i_C(t) = F.A.\delta.\left.\frac{\partial c(x,t)}{\partial t}\right|_{x=0} \quad (4)$$

Where δ is the double-layer capacitance thickness. And the diffusion equation is

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \qquad 0 < x < h \quad (5)$$

Finally the boundary condition is

$$\left.\frac{\partial c(x,t)}{\partial x}\right|_{x=h} = 0 \quad (6)$$

Now based on Equations 1, 2, 3, 4, 5, and 6, it can be shown that the admittance model ($Y(s) = \frac{I(s)}{V(s)}$) of a conjugated polymer [7].

$$Y(s) = \frac{s\left[\frac{\sqrt{D}}{\delta}\tanh(h\sqrt{s/D}) + \sqrt{s}\right]}{\frac{\sqrt{s}}{C} + Rs^{3/2} + R\frac{\sqrt{D}}{\delta}s\tanh(h\sqrt{s/D})} \quad (7)$$

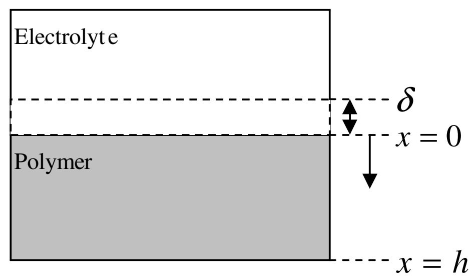

Figure 2 Description of frame assignment for diffusion.

2.2 Electromechanical Modelling

The electromechanical model relates the input voltage and displacement of the PPy actuators. It was shown that the relation between the induced in-plane strain (ε_c) and the density of the transferred charges (ρ) is as below [7, 12]:

$$\varepsilon_c = \alpha.\rho \quad (8)$$

Where α is the strain-to-charge ratio. Thus, the induced stress is

$$\sigma_c = \alpha.E_{PPy}.\rho \quad (9)$$

Where E_{PPy} is the Young's modulus of PPy. In the Laplace domain, ρ can be written as below [7, 10]:

$$\rho(s) = \frac{I(s)}{sWLh} \quad (10)$$

Where W is the width of the PPy, and L is the length of the PPy. The initial displacement Δy_m is caused by load (m) which can be obtained as below:

$$\Delta y_m = \frac{mgL}{WhE_{PPy}} \quad (11)$$

Where m, is the mass of applied load.

Finally based on Figure 3 and by combining Equations 7, 8, and 10 one can obtain the full model between input voltage (V) and output displacement (y) as below [7],[10]:

$$\frac{y(s)}{V(s)} = \frac{\xi}{sR + \frac{1}{C(1 + \frac{\sqrt{D}}{\delta\sqrt{s}}\tanh(h\sqrt{\frac{s}{D}}))}} \quad (12)$$

Where

$$\xi = \frac{1}{WLh} \tag{13}$$

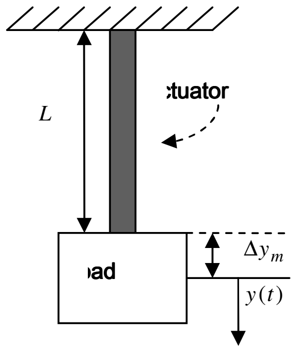

Figure 3 Description of frame assignment for displacement of the actuator.

By replacing the term tanh with its equivalent series in Equation 13 the actuator model is written as [7]:

$$\frac{y(s)}{V(s)} = \frac{\xi}{sR + \dfrac{1}{C\left(1 + \dfrac{2D}{h\delta}\displaystyle\sum_{n=0}^{\infty}\dfrac{1}{s + \pi^2 (2n+1)^2 D (2h)^{-2}}\right)}} \tag{14}$$

3 Experimental data

The experimental data has been obtained from [9]. Polypyrrole was used for test as EAP material and the electrolyte used was 0.1 M tetraethylammonium hexafluorophosphate (TEAPF6) in propylene carbonate (PC). The polymer film is held in the test fixture with clamps at the both ends. The reference electrode used in experiment was Ag/AgClO4. Mechanical loading is exerted by a voice coil actuator (Bruel & Kjaer Minishaker 4810). For the purpose of isotonic testing, a force transducer feedback control is used.

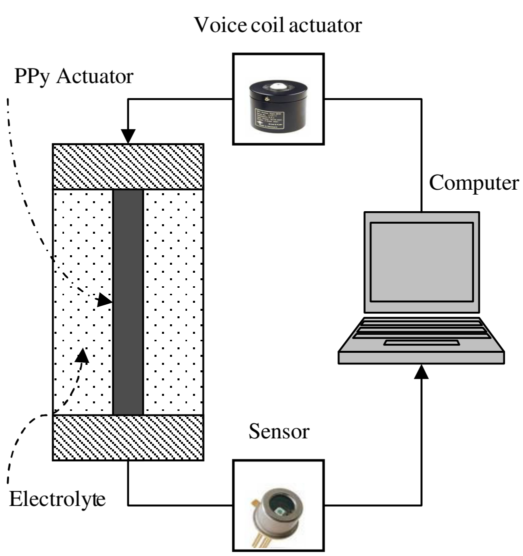

Figure 4 Schematic of the experimental setup.

The position sensor is photodiode (PPS-DL700-7PCBA) with a resolution of 250 nm. Figure 4 depicts the testing equipment. Typical values of physical parameters are presented in Table 1.

Table 1 Values of physical parameters

Parameter	Value
D	$1\times10^{-12} m^2/s$
h	$19\,\mu m$
R	800Ω
δ	$25\,nm$
C	$5.33\times10^{-5}\,F$

3.1 Isotonic testing based on voltage input

The voltage was increased in steps of 0.1 V starting from about -0.5 V vs. Ag/AgClO4 which is the potential of the zero charge (PZC).

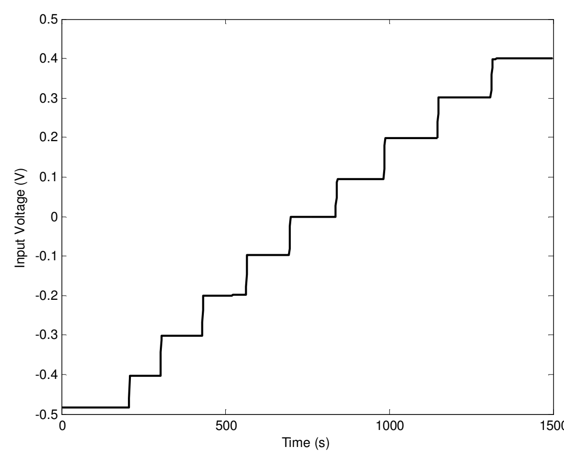

Figure 5 Input voltage applied to PPy actuator.

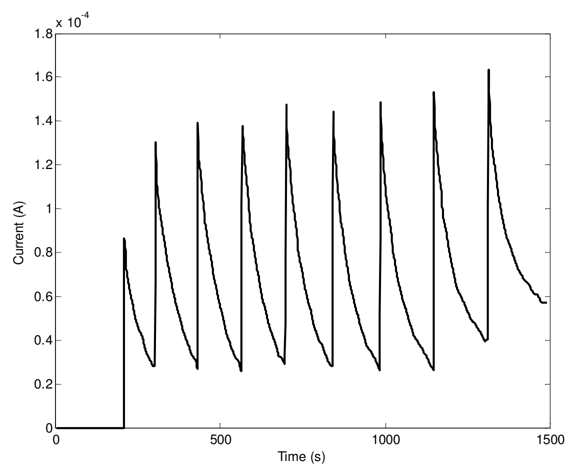

Figure 6 Experimental current output.

Subsequent to each potential step the current was permitted to drop down to 30 μA before the next step was applied. This value was reported to capture considerable section of the time response of the polymer electrical domain [8]. Figure 5 shows the potential input and Figure 6 depicts the current output of the actuator.

4 T-S Fuzzy modelling

Fuzzy logic was born in 1965 by Zadeh [13]. Nowadays, it is widely used in industrial applications. Fuzzy logic can model the nonlinear relationship between inputs and outputs. It can simulate the operator's behavior without use of mathematical model [14]. It is a method that transfers human knowledge into mathematics. Incomplete, vague and/or inaccurate expert knowledge is formulated with the aid of if–then rules. Each rule explains a nonlinear relationship between inputs and outputs. All rules together define a linguistic model [15, 16, 17]. The T–S fuzzy system is one of the most popular systems in model-based fuzzy control. It is described by fuzzy IF-THEN rules that represent local linear input–output relations of a nonlinear system. The T–S model is capable of approximating many real nonlinear systems, e.g., mechanical systems, electrical systems, chemical systems and so no. Because it uses linear models in the consequent part, linear control theory can be applied for system analysis and design consequently, based on the (PDC) approach [18]. The basic feature of T-S fuzzy modeling is to represent the local dynamic of system with a linear model, and the overall fuzzy model is combination of this linear model. One can represent the local linear systems as follows:

$$\begin{cases} \dot{x}_i(t) = A_i x(t) + B_i u(t) \\ y = C_i x(t) \end{cases} \quad i = 1,2,\ldots,r \tag{15}$$

Where (r) is the number of selected points for linearization. We consider the following T–S fuzzy system with (r) plant rules that can be represented as
Plant Rule i:

$$\textit{If } \tilde{z}_1 \textit{ is } \tilde{A}_1^i \textit{ and } \tilde{z}_2 \textit{ is } \tilde{A}_2^i \textit{ and},\ldots,\textit{and } \tilde{z}_p \textit{ is } \tilde{A}_p^i \textit{ Then},$$

$$\begin{cases} \dot{x}_i(t) = A_i x(t) + B_i u(t) \\ y = C_i x(t) \end{cases} \tag{16}$$

Where r is the total number of rules, $\tilde{Z}$ is the premise input vector and $\tilde{A}_p^i$ is a fuzzy set, then the fuzzy system can be given as

$$\dot{x}(t) = \frac{\sum_{i=1}^{r} \left(A_i x(t) + B_i u(t)\right) \mu_i(z(t))}{\sum_{i=1}^{r} \mu_i(z(t))} \tag{17}$$

Or

$$\dot{x}(t) = \left(\sum_{i=1}^{r} A_i h_i(z(t))\right) x(t) + \left(\sum_{i=1}^{r} B_i h_i(z(t))\right) u(t) \tag{18}$$

Where $\mu_i(z(t))$ is the fuzzy membership function and h can be defined as below

$$h^T = [h_1, \cdots h_r] = \left[\frac{1}{\sum_{i=1}^{r} \mu_i(z(t))}\right] [\mu_1, \cdots, \mu_r] \tag{19}$$

Since the term tanh in Equation 12 is not suitable for real time control of the actuator and this equation can not take into account the system uncertainties. In this paper T–S fuzzy model is used for purpose of modeling. As we shown in [3] a third order model can well describe the actuation process. The experimental data shows that a LTI model based on the initial physical parameter of the actuator can not accurately predict the behavior of the actuator, thus based on observation of the experimental data we consider three zones for the actuation process. These zones which some how indicate the variation of the physical parameter of the actuator are chosen as the premise of our T-S fuzzy model. We name these zones: initial, middle, and final zone. Corresponding membership functions for these zones are depicted in Figure 7. For example the linear system in the initial zone is as below:

$$A_1 = \begin{bmatrix} -0.918 & -0.087 & 0 \\ 0.125 & 0 & 0 \\ 0 & 0.125 & 0 \end{bmatrix} \; ; \; B_1 = \begin{bmatrix} 0.0039 \\ 0 \\ 0 \end{bmatrix}$$

$$C_1 = \begin{bmatrix} 0 & 0.0061 & 6.68 \times 10^{-6} \end{bmatrix}.$$

Since our model is going to be used as a multi purpose model and be able to satisfy the rules needed to implement the PDC controlling approach, the polypyrrole actuator dynamic must be controllable. This can be checked using the controllability test matrix Φ_c .

$$\Phi_c = \begin{bmatrix} B & AB & \cdots & (A)^{n-1} B \end{bmatrix}$$

$$= \begin{bmatrix} 0.0039 & -0.00358 & 0.003249 \\ 0 & 0.00048 & -0.00044 \\ 0 & 0 & 0.000061 \end{bmatrix}$$

Clearly the rank of Φ_c is three, thus the system is controllable.

Comparison of experimental data with the T-S fuzzy model and DEM model is shown in Figure 8.

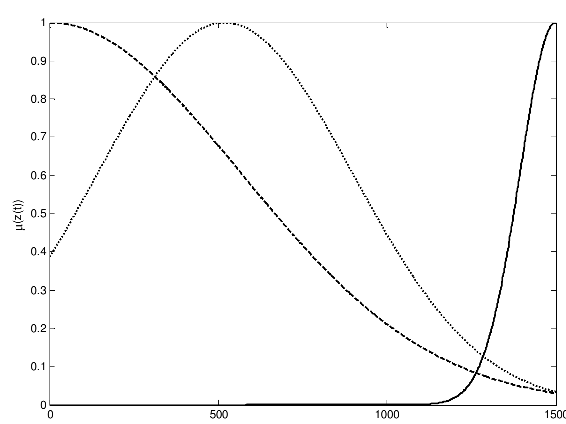

Figure 7 Membership function for the fuzzy zones.

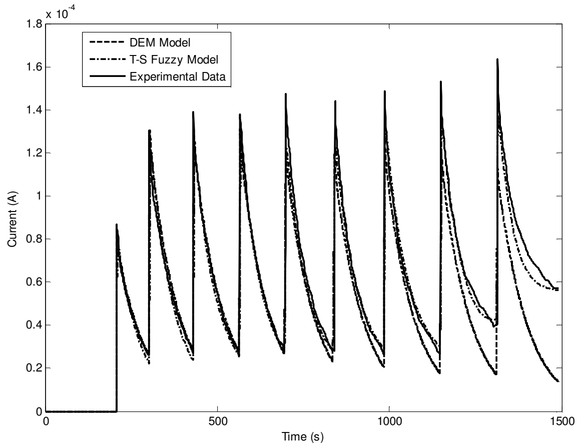

Figure 8 Comparison of experimental data with the T-S fuzzy model and DEM model.

5 Design of a multi-level Fuzzy-QFT controller

There are two different methods to guarantee the stability of a fuzzy control system. The first technique requires designing the control system in the way that the closed-loop system with fuzzy controller is stable. In the second approach, the fuzzy controller is designed first without considering the stability conditions and next another controller is appended to the fuzzy controller to take care of stability conditions [16]. In this paper we chose QFT as a second-level controller which guarantee the stability of the system while the main controller is a fuzzy controller Figure 9. Therefore, if the fuzzy controller works well, the QFT controller is idle; if the system tends to be unstable, the QFT controller starts working to guarantee stability.

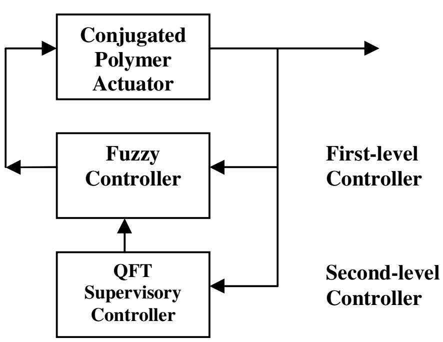

Figure 9 Architecture of two-level Furry-QFT controlling system

Now we define the total controlling output as below:

$$u = u_{fuzzy} + \Psi \times u_{QFT} \quad (20)$$

Where u_{fuzzy} is the fuzzy controller output, u_{QFT} is the QFT controller output, and Ψ is the indicator function with following formula:

$$\Psi = \begin{cases} 0 & |T| < m \\ \dfrac{|T| - m}{M - m} & m \le |T| < M \\ 1 & |T| \ge M \end{cases} \quad (21)$$

Where $|T|$ is magnitude of the closed-loop system, m, and M are lower and upper bound for it respectively.

5.1 Design of Fuzzy controller

We use a proportional-derivative fuzzy control system [19]. The fuzzy control system has two inputs, namely error, and differential of error. The linguistic values NB, NM, NS, ZE, PS, PM, and PB are the same for inputs and output. The fuzzy inference system is Product Inference Engine with following parameters: (i) individual-rule based inference with union combination, (ii) Mamdani's product implication, (iii) algebraic product for all the t-norm operators and max for all the s-norm operators. We also used singleton fuzzifier, center average defuzzifier, and Gaussian membership functions. For example the error membership function is shown in Figure 10.

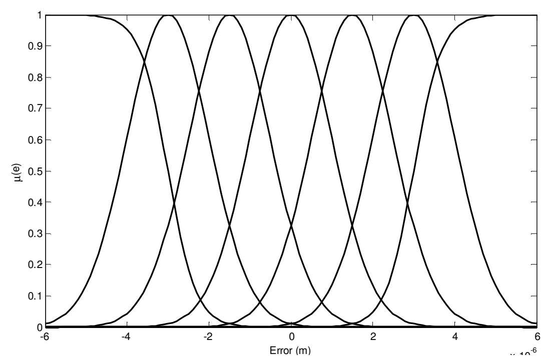

Figure 10 Membership function for error.

Assuming that there are seven membership functions on each input universe of discourse, there are 49 possible rules which are shown in Table 2.

Table 2 Complete set of rules for Fuzzy controller

U_i \ $\dot{E}_i$ / E_i	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZO
NM	NB	NB	NM	NM	NS	ZO	PS
NS	NM	NM	NS	NS	ZO	PS	PM
ZO	NM	NM	NS	ZO	PS	PM	PM
PS	NM	NS	ZO	PS	PM	PM	PB
PM	NS	ZO	PS	PM	PM	PM	PB
PB	ZO	PS	PM	PM	PM	PB	PB

In order to optimize the performance of the fuzzy controller we used Genetic Algorithm (GA) for tuning the output membership functions. The fuzzy controller output surface is depicted in Figure 11. Figure 12 shows the fuzzy controller block diagram.

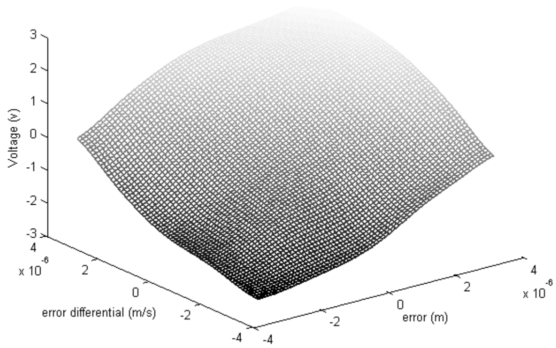

Figure 11 Fuzzy controller output surface.

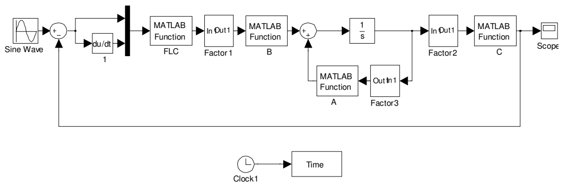

Figure 12 Fuzzy controlling block diagram

5.2 Design of QFT controller

Quantitative Feedback Theory (QFT) is a robust feedback control-system design technique initially introduced by Horowitz (1963, 1979), which allows determination and evaluation of closed-loop robust performance as well as stability specifications. Since then this technique has been developed by him and others [20], [21], [22], [23].

In parametric uncertain systems, we must first generate plant templates prior to the QFT design (at a fixed frequency, the plant's frequency response set is called a *template*). Given the plant templates, QFT converts closed loop magnitude specifications into magnitude constraints on a nominal open- loop function (these are called QFT *bounds*). A nominal open loop function is then designed to simultaneously satisfy its constraints as well as to achieve nominal closed loop stability. Design of a QFT controller can be a difficult job, but when it is used as a second-level controller which must guarantee the stability of the system, design procedure is much simpler. As a second-level controller, QFT controller must guarantee the stability of the system, when the output is far from the desired response. In medium and small error ranges, the desired performance of the output response will be achieved by Fuzzy controller. The quantitative approach provides a design methodology which enables the designer to observe clearly the limitations and trade-offs in its design. A realistic definition of optimum in LTI systems is the minimization of the high-frequency loop gain while satisfying the performance bounds. On the other hand design of a QFT controller, which exactly lies on the performance bounds is a difficult job and sometimes impossible. Therefore application of the QFT as a second-level controller will simplify the loop shaping phase of design.

The robust margin is that the magnitude of closed loop system for all considered uncertainty must be less than 1.1, and the robust tracking specifications are overshoot (=5%) and setteling time (=0.4 s).

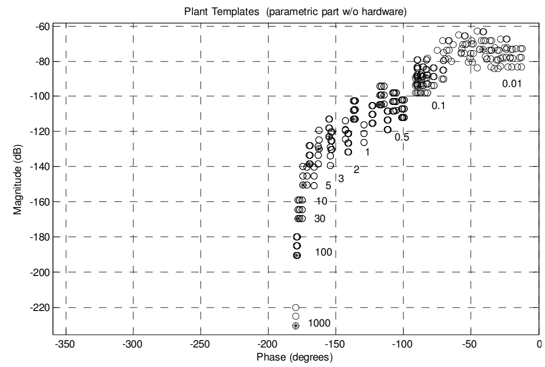

Figure 13 The boundary of the plant templates

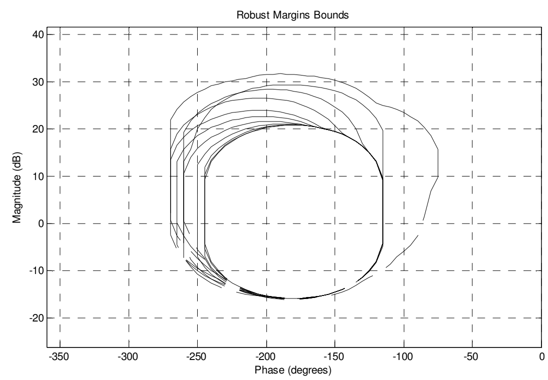

Figure 14 Robust margin

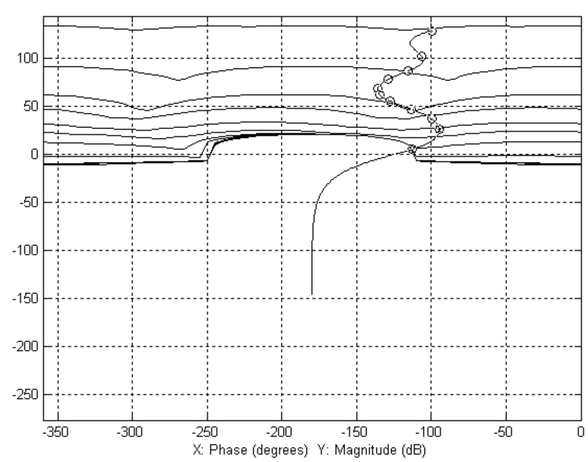

Figure 15 Loop shaping of open-loop system

At the first step we must define the plant uncertainty (template), which is shown in Figure 13. Then by having robust margin bounds in the loop-shaping phase of design suitable controller can be achieve as follows:

$$G = 1869754\frac{(s+5.44)(s+0.03532)}{(s+2422)(s+0.00283)} \quad (22)$$

Robust margin bounds are shown in Figure 14. Figure 15 depicts the loop-shaping of open loop system. Figure 16 shows the robust stability of closed-loop system, which indicates the robust stability of the closed-loop system under QFT controlling approach.

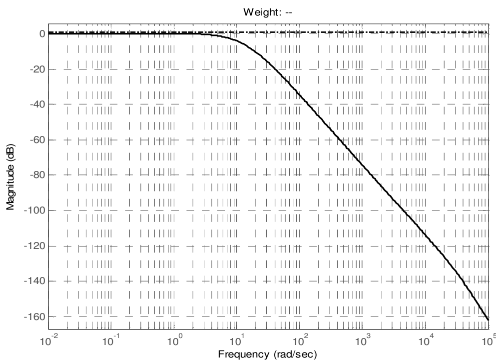

Figure 16 Robust stability of closed-loop system

In order to show the effectiveness of our designed fuzzy controller we run simulation for tracking problem in all of three fuzzy zones. Figures 17-a, 17-b, and 17-c show the tracking problem for the reference input $R = 2\times10^{-5}\sin(0.1\pi t)$ (meters). Figures 18-a, 18-b, and 18-c depict the tracking error.

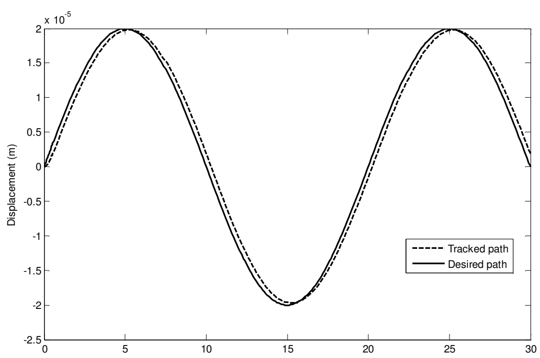

Figure 17-a Tracking problem for sin wave in the first fuzzy zone

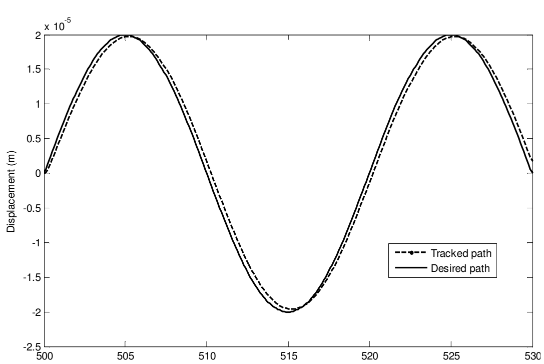

Figure 17-b Tracking problem for sin wave in the second fuzzy zone

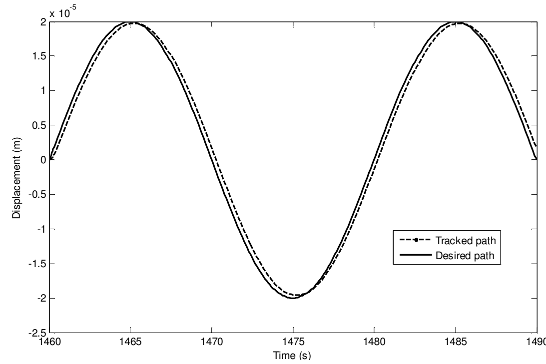

Figure 17-c Tracking problem for for sin wave in the third fuzzy zone

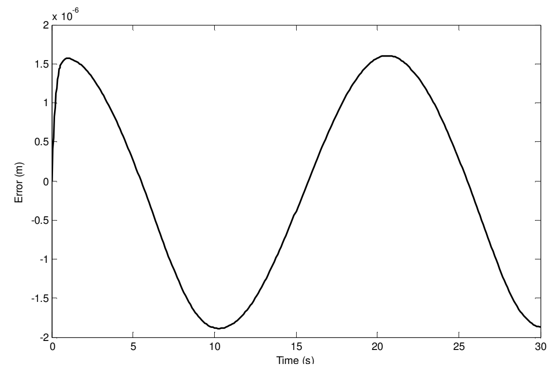

Figure 18-a Tracking error for the first fuzzy zone

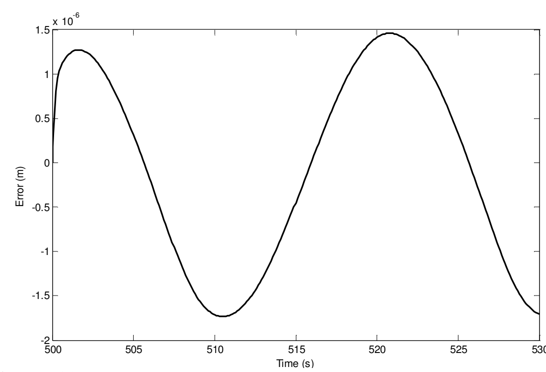

Figure 18-b Tracking error for the second fuzzy zone

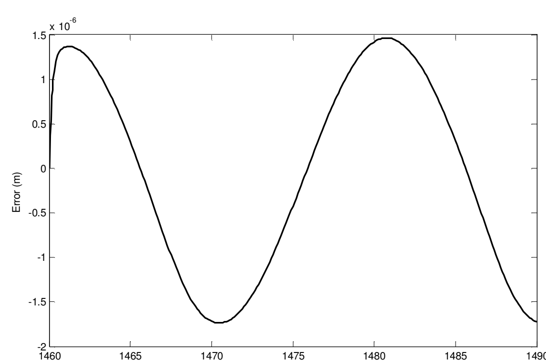

Figure 18-c Tracking error for the third fuzzy zone

6 Conclusions

The main contributions of this paper are:

(i) in the modeling part based on the application of the T-S fuzzy modeling, the system uncertainties are incorporated into the model. Comparison of the experimental data with our proposed T-S fuzzy model indicates that, it could greatly predict the actuation process over the variation of actuator physical parameter. Generally we can state that by proposing T-S fuzzy model, the obstacles behind conventional modeling techniques (DEM, RD) such as model parameter variation and other constrains and assumptions are tackled successfully.

(ii) in the controlling part we used multi-level Fuzzy-QFT controlling approach. Because QFT controller is a supervisor which guarantees the stability of the system, the loop shaping phase of design is simplified. Additionally, we have much more flexibility in design of fuzzy controller. Results of simulation over all of the three fuzzy modeling zones, show that the proposed controlling scheme has consistent tracking performance despite the existence of uncertainty in the dynamic of the actuator.

7 Literature

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