FUZZY LOGIC ADAPTIVE CONTROLLERS

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ABSTRACT
In this paper fuzzy logic (FL) is used to develop adaptive controllers. FL will replace well-known adaptive schemes. We have addressed both the MIT rule based and Lyapunov approach based Model Reference Adaptive Controllers (MRACs). Simulations are carried out to illustrate the developed schemes and their performance with uncertain parameters.

1 Introduction
FL is a logic that is close to the human thinking and reasoning and provides a means for modeling and dealing with the inexact nature of the real world. FL is introduced by Zadeh [1]. It tries to capture experience and intuition in the form of IF-THEN rules from which conclusions are drawn. Fuzzy logic control is a technology in which FL is used to develop control strategies for dynamical systems.
In using FL for control purposes, one is faced with the following alternatives. The first is to design a Fuzzy Logic Controller (FLC) based on the input-output behavior of the system under study [2,3,4,5]. Another option is to use FL to tune the parameters of classical control schemes such as the PID, VSC etc. [6,7]. The third option is to use FL to mimic the behavior of some classical controllers such as the PID controller [7]. In this paper we have adapted the third alternative. FL is used to replace some MRACs [8,9], namely the MIT rule based Model Reference Adaptive Controller (MRAC) and the Lyapunov approach based MRAC. We have developed the schemes and have presented some simulation results.
In the following section we present some background material on the two adaptive schemes that we plan to replace with a FLC. In section 3, we give the FL adaptive schemes. Simulation results are shown for one parameter and two parameter adjustments. Finally we conclude our paper in section 4.

2 Background
Adaptive control is one of the methods available in the literature to control systems with uncertainties [10]. Several adaptive schemes are reported in the literature together with a lot of successful applications [10,12]. MRACs form a major body of adaptive controllers. Among the available MRACs the MIT rule based MRAC and the Lyapunov approach based MRAC are considered. In the following, we present the basic principle of these adaptive controllers.

2.1 MIT Rule
Given a system

$$y_p(s) = G_p(s,k)\ u(s)$$

where k is an unknown vector of n parameters. We desire to adjust the parameter k_c in order to force the output $y_p(t)$ follows the output of a reference model $y_m(t)$ given by

$$y_m(s) = G_m(s)\,u(s)$$

In the MIT rule [10] based method, this is achieved by minimizing the objective function

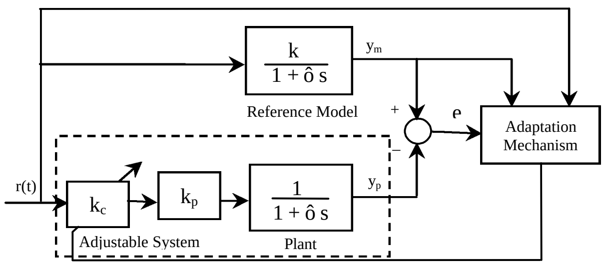
$$J = \frac{1}{2}\left\|y_m - y_p\right\|^2 \qquad (1)$$

The adjustment law for parameter k_c is given by

$$\dot{k}_c(t) = -g\ \{y_p(t) - y_m(t)\}\frac{\partial\, y_p(t)}{\partial\, k_c} \qquad (2)$$

where g is a constant, which determines the rate of gradient adaptation
Consider a simple MRAC as shown in Fig. (1). The objective is to adjust k_c such that the product of the system gain k_p and k_c eventually be equal to model gain k.
For the MIT adaptive controller in Fig.(1) , Eq. (2) may be replaced by

$$\dot{k}_c(t) = -g\{y_p - y_m\}\ y_m(t) \qquad (3)$$



Fig(1): Gain Adaptation MRAC

2.2 Lyapunov Approach

Stability is an important factor to be considered in MRAC design. In the previous design method, large inputs or large gains can cause instability. Lyapunov [10,12] approach invariably includes stability aspect in the controller design. In the Lyapunov approach first we obtain the differential equation that describes the error between the output of the reference model and that of the plant. The objective is to obtain parameter-adjustment equations that assure that the differential equation describing the error is asymptotically stable. To do this, a positive definite Lyanunov function is formulated for the error equation. The adaptation mechanism equations are then selected so as to cause the time derivative of the Lyapunov function to be negative definite.

Lyapunov's stability theorems make possible a method of synthesizing the control laws to result in a design that guarantees stability. The type of solution depends on the form of Lyapunov function selected. The system will be stable in the sense that the tracking error goes to zero or remains bounded, as when disturbances or time-varying parameters are involved.

Let us consider the following model and plant

$$G_p = \frac{k_p k_c}{t\,s+1} \qquad \text{where } k_c \text{ is adjustable}$$

$$G_m = \frac{k}{t\,s+1}$$

The error between the model and plant output to an input signal *r* is

$$e = y_m - y_p$$

$$\dot{e} = \frac{1}{t}\left\{-e + \left(k - k_c k_p\right) r\right\} \qquad (4)$$

Let us assume

$$x = k - k_c k_p, \quad \text{so} \quad \dot{x} = -\dot{k}_c k_p$$

We may now select the Lyapunov function as

$$v = e^2 + l x^2 \qquad \text{for positive } \lambda$$

The derivative w.r.t. time can be written as

$$\dot{v} = -\frac{2}{t} e^2 + 2x\left\{\frac{1}{t} e r + l \dot{x}\right\} \qquad (5)$$

To make sure that $\dot{v} < 0$, we may use

$$\dot{x} = -\frac{1}{t\,l} e r \qquad \text{which gives}$$

$$\dot{k}_c = \frac{1}{t\ l\ k_p} e\,r = \Psi\, e\,r \qquad (6)$$

3 Fuzzy Logic Controllers

FL is based on the fuzzy set theory. Fuzzy sets are defined as the sets that do not have crisply defined membership but, rather, allow objects to have grades of membership from 0 to 1 [1]. A fuzzy set is defined by a label and a membership function. Their are four main building blocks of a FL controller: *Fuzzification, Fuzzy rule base, Inference engine*, and *De-fuzzification.*

Fuzzification is the process of transforming the range values of the variables of interest into the corresponding universe of discourse, and then converting the data into suitable linguistic variables. *Fuzzy rule base* is the collection of rules that are expressed as fuzzy conditional statements IF (Antecedent) THEN (Consequent). *Inference engine* is a mapping from fuzzy sets in the input space to fuzzy sets in the output space. *De-fuzzification* involves converting the inferred fuzzy output into a crisp value and then scaling that crisp value into a suitable range.

3.1 Single Parameter MIT Rule Based FL-MRAC

For MIT rule based gain adjustment MRAC, the error signal and the output of the model are required to update the gain. For the FL counter part we are again going to use the error signal and the model output as the input to the FL-MRAC which generates a corrective output signal as shown in Fig.(2).

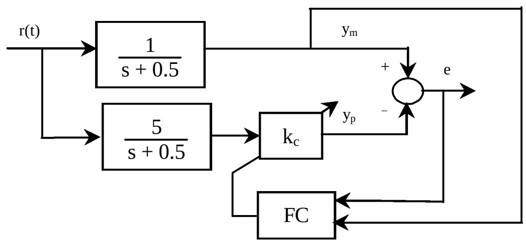


Fig.(2): MIT rule based FL-MRAC

For FLC design, operator's opinion about the performance of the system is required. To obtain this knowledge we have applied different inputs to both model and the plant and observed the error signal, model output and the corresponding MIT rule based control signal. On the bases of these observations we have defined membership functions (msf). Membership function for each variable partition the range into linguistic descriptors that overlap. We have used triangular msf for all applications. For this application we have selected 3 msf for model output, 7 msf for error and 7 msf for controller output.

After selecting and defining the msf, fuzzy control rules were delineated. A general rule for the fuzzy controller can be described as follows:

{if e is A_i and y_m is B_i then make decision C_i}

The crisp (defuzzified) output signal of the fuzzy controller is obtained by calculating the centroid of all fuzzy output variables.

Input of magnitudes 4, 24, 0 and 16 were applied at time instant 0, 15, 30 and 45 seconds respectively. In the beginning there is some difference in the plant and model outputs. But after 2 seconds the plant has started to emulate the model and no further error between the plant and the model outputs is observed as shown in Fig.(3).

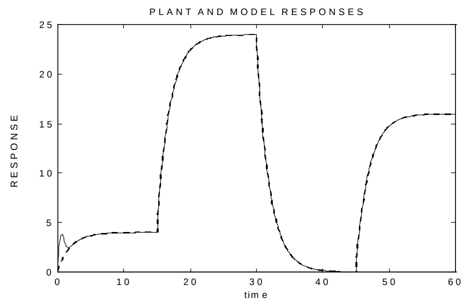


Fig.(3): Plant and model responses

3.2 Single Parameter Lyapunov Approach Based FL-MRAC

For Lyapunov approach based gain adjustment FL-MRAC, the input applied to the model and error are the two controller inputs as shown in schematic in Fig.(4). We have selected 3 msf for plant input, 7 for error and 7 for the controller output. The decision table is the same as for MIT rule based FC.

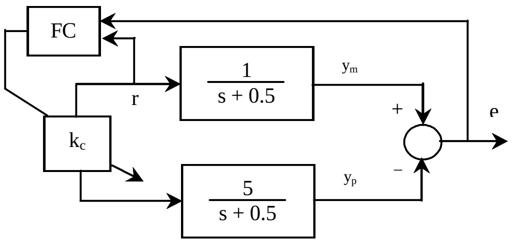


Fig.(4): Lyapunov apporach based FL-MRAC

For performance study, inputs of magnitude 2,12,0 and 8 at time instance 0,15,30 and 45sec respectively were applied. Here again after 2 seconds plant has started to follow the model.

3.3 Two Parameter Lyanunov Approach Based FL-MRAC

Let's consider the following plant and model

$$G_P = \frac{a}{s+b}$$

$$G_m = \frac{c}{s+d}$$

The plant parameters *a* and *b* are the two adjustable parameters whereas model parameters *c* and *d* are fixed. The input applied to the plant is:

$$u = k_y y_p + k_r r$$

Fig.(5) shows the block diagram of the scheme. For this case the parameters to be adjusted are the loop gain and the feedback gain of the controller. Two separate controllers are designed to adjust these parameters. For loop gain, error and the input are the two controller inputs. We have selected 5 msf for error, 4 for input and 7 for change in loop gain. The msf are shown in Fig.(6). The decision table is also shown below.

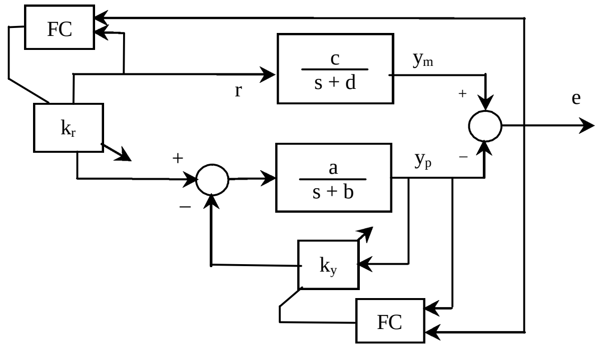


Fig.(5): Two parameter Lyapunov approach based FL-MRAC

Table (1): Decision Table for Loop Gain

u \ e	NL	NM	Z	PM	PL
Z	PL	PL	Z	NL	NL
S	PL	PM	Z	NM	NL
M	PM	PS	Z	NS	NM
L	PS	PS	Z	NS	NS

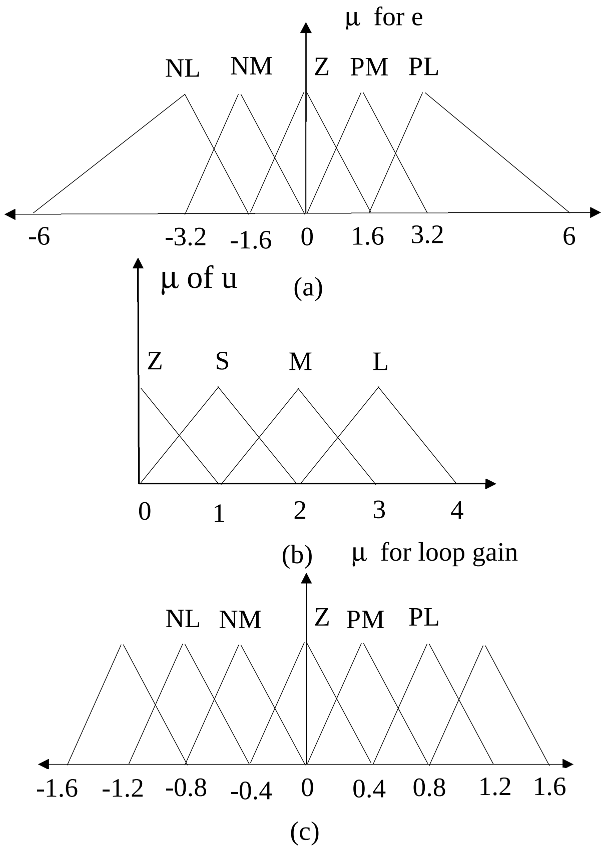


Fig.(6): (a) msf for error (b) msf for input (c) msf for loop gain

Similarly for the feedback gain, error and the plant output are the inputs of the controller and change in feedback gain is the output of the controller. We have selected 5 msf for error, 7 for plant output and 7 for change in feedback gain.

The decision table and the msf are shown in the Fig.(7).

Table (2): Decision Table for Feedback Gain

ym \ e	NL	NM	Z	PM	PL
NL	NS	NS	Z	PS	PS
NM	NM	NS	Z	PS	PM
NS	NL	NM	Z	PM	PL
Z	Z	Z	Z	Z	Z
PS	PL	PM	Z	NM	NL
PM	PM	PS	Z	NS	NM
PL	PS	PS	Z	NS	NS

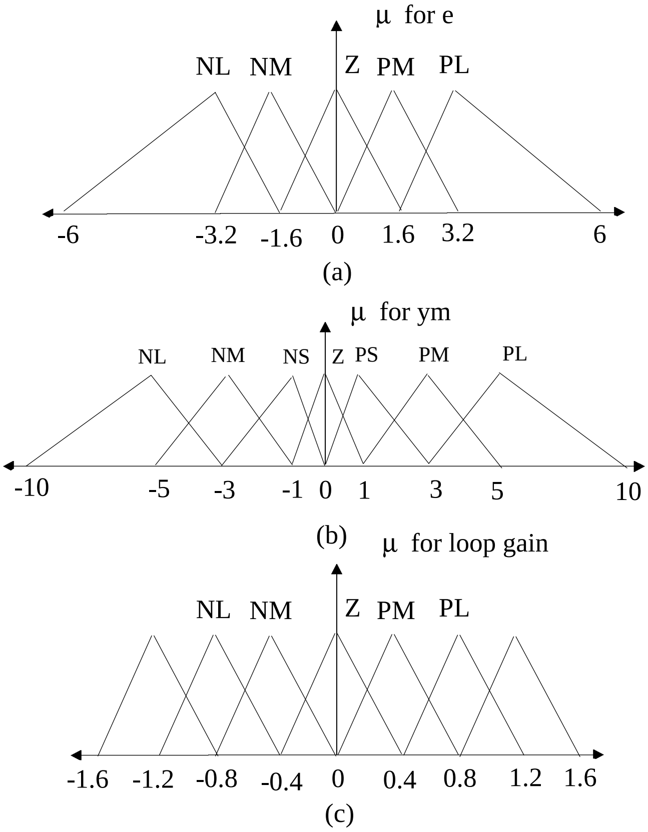
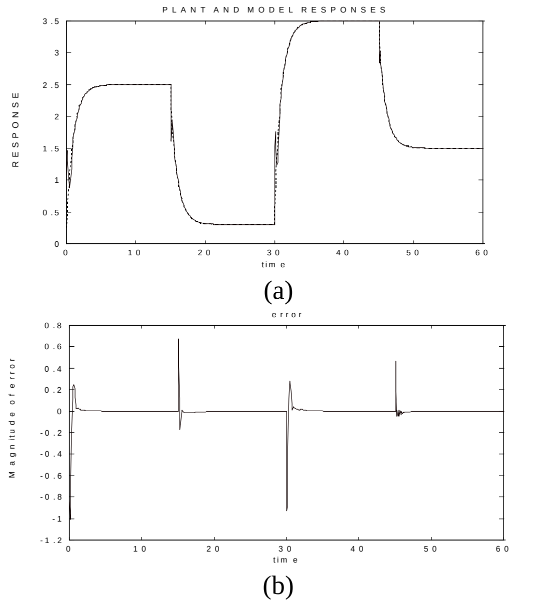


Fig.(7): (a) msf for error (b) msf for model output (c) msf for feedback gain

From the results we see that, at first plant starts to follow the model in about 3 seconds. If for the model *c* and *d* have a value of 1 then in 3 seconds, three time constants have been elapsed, so we are near steady state. At this time, the updated steady state value of plant $(a*K_r)/(b+K_y)$ and model c/d are same. Now once the input applied is changed, due to different time constants $1/(b+K_y)$ and $1/d$ for plant and model, again the responses mismatch and error is observed as depicted by Fig.(8) at time t=15, 30 and 45 seconds. Again the plant parameters *a* and *b* will be updated. After a few updating the parameters *a* and *b* will become very close to model and then we see relatively less error as the input is switched from one value to the other. A sinusoidal uncertainty of the form $M\sin(kp\,t)$ has been added to the adjustable parameters of the plant. Fig(8) shows the plant and model responses and the error signal.



Fig(8): (a) Plant and model responses (b) Error b/w model and plant responses

3.4 Two Parameter Lyanunov Approach Based FL-MRAC for Second Order System

We have the following second order plant and model:

$$G_p(s) = \frac{a}{s^2 + bs + c}$$

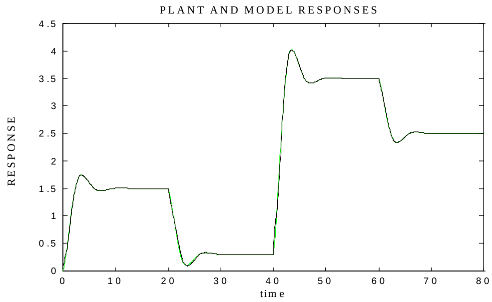
where a,b,c are unknown parameters

$$G_m(s) = \frac{1}{s^2 + s + 1}$$

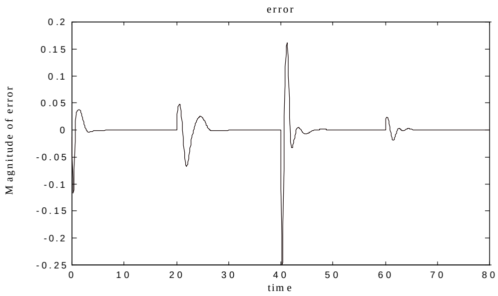
The schematic is same as Fig(5), the only difference is a 2nd order plant and model. To update the feedforward and the feedback gains we use the Lyapunove approach based scheme. Inputs for feedforward gain FC are the error and the input and for the feedback gain FC are error and the output of the plant.

For this application we have used the same decision table and number of msf for inputs and outputs as for the two parameters (first order) Lyapunov based FL-MRAC. Only the ranges of the inputs and msf are changed. For feedforward gain control, ranges for error, input and output are (-4.8-4.8), (0-4), and (-1.6-1.6) respectively. For feedback gain control, ranges for error, output of the plant and output of the FC are (-4.8-4.8), (-10-10), and (-2.4 -2.4) respectively.

To investigate the performance, step inputs of varying magnitude are applied to both the model and the plant, a sinusoidal disturbance of the varying magnitude was added to different parameters of the plant. The results in Fig.(9), have shown that after 4 seconds the plant has started to follow the model. It is also obvious from the results that after a few fluctuations of the applied input, the parameter of the model and the plant become very close and very little error is observed on further switching of the inputs.



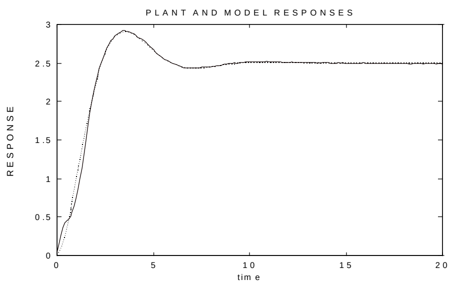
(a)



(b)

Fig(9): (a) Plant and model responses (b) Error b/w model and plant responses

For a second simulation a zero mean unity variance random noise is added to the plant input together with the above mentioned uncertainties. The results in Fig.(10) illustrate the robustness of the controller.



Fig(10): Plant and model responses

4 Conclusions

Four Fuzzy Logic Controllers are developed. First FLC replaces the MIT rule based MRAC. For this, error signal and output of the model are selected as FLC inputs. The output of the FLC adjusts the loop gain. For the same plant and model Lyapunov approach based FL-MRAC is designed. The performance of the controller is evaluated by applying inputs of varying magnitude plus a sinusoidal uncertainty in the plant. The results show the effectiveness of the FLC to force the plant to follow the model, under uncertainties.

A two parameter: one feedback gain and other loop gain, Lyapunov approach based FL-MRAC is also designed. For loop gain control, input to the model and error are the inputs to the 1st FC. And for feedback gain control, output of plant and error are the inputs of 2nd FC. For the second order system we have adjusted the feedforward gain and feedback gain and used the same scheme as for two-parameter Lyapunov approach based FL-MRAC. Simulations with different inputs and disturbances are carried out. The results obtained, show the effectiveness and robustness of the scheme.

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