DESIGN OF FUZZY ADAPTIVE CONTROLLERS OF REDUCED RULE BASE

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Abstract

This paper describes a method to design rule-based fuzzy adaptive controllers. The rules are learnt from the observed behaviour of a virtual self-tuning feedback (PID) controller. The designed controller is supposed to support typical control requirements (i.e. fast-following, zero steady state error, overshoot suppression, etc.) using only a small number of rules.
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1 INTRODUCTION

Nowadays, there are more than 30000 publications about fuzzy set theory and its applications. These are the result of an intensive research work that has been carried out during the last two decades. There have been proposed many methods, algorithms and techniques to apply fuzzy technologies to a variety of applications. One of the problems of having such amount of information is the lack of standardisation. This has given rise to a situation where the same term is used to name different methods, the same algorithm is given different names and various incompatible solutions to the same problem are offered by different fuzzy systems manufactures. To solve this problem, some international organisations like ISO (International Standardisation Organisation) and IEC (International Electrotechnical Commission), are drafting standards on fuzzy systems.

The IEC proposal [2] (referred as IEC 1131-7) is aimed at using the *basic fuzzy logic functionality* in industrial equipments of different manufactures keeping portability among them. At the moment, IEC has defined a basic fuzzy systems description language and the draft of the standard is still opened to new amendments from control equipment manufactures.

From the point of view of this article, two implementation issues are the most important characteristics of the IEC proposal:

- It will make easier to move fuzzy system implementations from one hardware platform, or software tool, to another.
- It includes a way of defining adaptive fuzzy controllers by supporting 'on-line' variable membership functions.

In this article a method will be proposed to design adaptive fuzzy controllers taking into account IEC restrictions on membership functions and keeping in mind it could be implemented on PLC's using the control languages defined by the IEC 1131-3 standard [1].

1.1 IEC LANGUAGE FOR FUZZY CONTROL

As it has been noted, one of the most relevant topics of the IEC standard is the definition of a language for the specification of fuzzy control systems. This language is an extension to the control languages defined in the IEC 1131-3 standard. A fuzzy control system is specified as a *Function Block* with four subsections: (a) *variable section*, (b) *fuzzification section*, (c) *defuzzification section*, and (d) *rule base section.*

The structure and syntax of this function block is shown in Figure 1. Input and output variables are declared using the VAR_INPUT and VAR_OUTPUT sections of the function block. For fuzzy input variables, their membership functions are defined in the *Fuzzification* section using the following syntax:

```
FUZZIFY variable_name
   TERM term_name := membeship function;
END_FUZZIFY
```

The name of the fuzzy input variable must be placed after the keyword FUZZIFY. Each linguistic term of the variable is defined using the keyword TERM, followed by the name of the term and a piece-wise linear membership function specified as a table of points. Every point of the membership function is formed by a pair of values: the input variable value and the membership degree of the variable to the linguistic term. All the points must be specified in ascending order of the variable value and, as the membership function is linear between two consecutive points, the membership degree of a specific crisp value of the input variable is calculated by linear interpolation. Using this syntax all basic membership functions (i.e. ramp, triangle) can be defined.

```
FUNCTION_BLOCK Fuzzy_FB
VAR_INPUT
   Temp:REAL;  Pressure:REAL;
END_VAR
VAR_OUTPUT
   valve:REAL;
END_VAR
FUZZIFY temp
   TERM cold := (3, 1) (27, 0);
   TERM hot := (3, 0) (27, 1);
END_FUZZIFY
FUZZIFY pressure
   TERM low := (55, 1) (95, 0);
   TERM high := (55, 0) (95, 1);
END_FUZZIFY
DEFUZZIFY valve
   TERM drainage := -100;
   TERM closed :=0;
   TERM inlet  :=100;
   ACCU: MAX;  METHOD: COGS; DEFAULT := 0;
END_DEFUZZIFY
RULEBLOCK N1
   AND: MIN;
   RULE 1: IF temp IS cold AND pressure IS low
            THEN valve IS inlet
   RULE 2: IF temp IS cold AND pressure IS high
            THEN valve IS closed WITH 0.8;
   RULE 3: IF temp IS hot AND pressure IS low
            THEN valve IS closed;
   RULE 4: IF temp IS hot AND pressure IS high
            THEN valve IS drainage;
END_RULEBLOCK
END_FUNCTION_BLOCK
```

Figure 1: Fuzzy function block definition according to IEC 1131-7 standard

Adaptive fuzzy control is also possible by on-line variation of the base points of any membership function. This can be done using some crisp input variables of the function block as points of the membership function. An example of how to use input variables in this way is given in Figure 2.

```
VAR_INPUT
   temp: REAL; pressure: REAL;
   /* inputs for on-line adaptation */
   bp_warm1, bp_warm2: REAL;
END_VAR
FUZZIFY temp
   TERM warm := (bp_warm1,0.0), (21.0,1.0),
                (bp_warm2,0.0);
             .......
END_FUZZIFY
```

Figure 2: Adaptive fuzzy procedure according to IEC 1131-7 standard

The IEC adaptive method uses a lookup table to store and modify the base points of membership functions. In the following sections an automated method of getting this values is described. This method comprises the following steps:

- On-line virtual controller design (in this paper a PI(D) second-order linear controller is used).
- Fuzzy rule-based controller training using the knowledge gathered from the virtual controller.
- On-line application of the fuzzy rule based controller (this controller could be implemented on a IEC 1131 compliant PLC).

2 ONLINE VIRTUAL CONTROLLER DESIGN

The first step of the method consists in designing a virtual controller that will be used as a trainer for getting the fuzzy controller rule-base. This virtual controller must satisfy some dynamic requirements like to increase operational speed while keeping reduced steady state error, to avoid overshoot, etc. Several well-known design techniques are available to accomplish this task:

- Relay feedback auto-tuning.
- Frequency domain design by FFT application.

2.1 VIRTUAL CONTROLLER DESIGN

As example, an approximate method called the method of harmonic balance is used. This method is based in relay feedback auto-tuning. Figure 3 shows a process transfer function with a feedback ideal relay. The virtual controller (a PID is used in this example) is placed in parallel with the feedback relay.

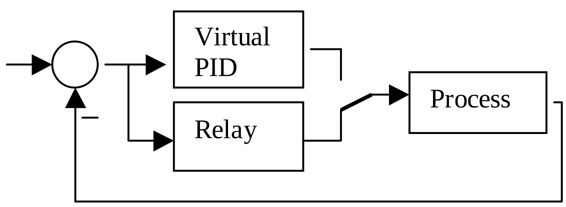

Figure 3: Block diagram of a relay auto-tuner

The approximate condition for oscillation can be determined by assuming that there is a limit cycle with period T_u and frequency $W_u = 2\pi/T_u$ such that the relay output is a periodic symmetric square wave. If the relay amplitude is d, a simple Fourier series expansion of the relay output shows that the first harmonic component has the amplitude $4d/\pi$. If it is also assumed that the process dynamics are like those of a low-pass system and that the contribution of the first harmonic rules the output. The amplitude of the error signal is given by

$$a = \frac{4d}{\pi}\left|G(iWu)\right| \qquad (1)$$

The condition for oscillation is given by

$$\arg G(iWu) = -\pi \qquad (2)$$

and the ultimate gain is calculated as

$$Ku = \frac{4d}{\pi a} = \frac{1}{|G(iWu)|} \qquad (3)$$

where K_u can be regarded as the equivalent gain of the relay for transmission of sinusoidal signals with amplitude *a*. The parameters *d, a* and T_u are shown in Figure 4.

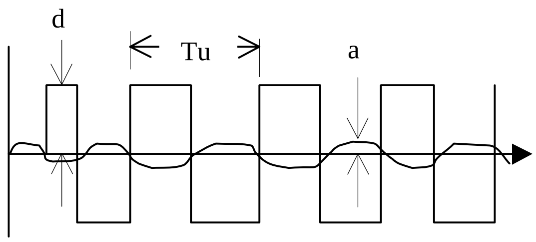

Figure 4: Parameters of the harmonic balance auto-tuner

Using the relay technique, only two parameters of the virtual controller: K_u and T_u, have been obtained. The parameters of a PID controller can be calculated from K_u and T_u using the tuning method of Ziegler-Nichols. Table 1 shows the relationship between K_u and T_u and the PID parameters: K_p, T_i and T_d.

Table 1: Vitual PID parameters

K_p	T_i	T_d
0.6*K_u	0.5*T_u	0.12*T_u
K_p	**K_i**	**K_d**
0.6*K_u	1.2*K_u/T_u	0.72*K_u*T_u

2.2 LEARNING FUZZY RULES

The virtual controller will be used as a trainer of the fuzzy rule-based controller. At this stage it is necessary to take into account that the membership functions of the rule base must be linear functions in order to fulfil the requirements of the IEC standard. There are several fuzzy reasoning methods classified into two categories: direct methods and indirect methods. The most popular are the direct ones:

- Mamdani direct method [3].
- Fuzzy modelling procedure of Takagi&Sugeno [4][5].
- Simplified method.

From these, the fuzzy modelling procedure of Takagi&Sugeno uses linear functions in the conclusion of the rules, so it is the best suited for our purposes. The format of the Takagi&Sugeno rules is

IF *x* is *A* **AND y** is *B* **THEN** $z = ax + by + c$

where a, b and c are the parameters of the linear function in the consequent of each rule. As defined by Takagi&Sugeno, the rule base structure needed to implement a conventional PID controller using a fuzzy controller is given in Table 2. The fuzzy rule base (Table 3) is achieved by applying the additive property to the consequent of each rule of Table 2.

Table 2: Fuzzy modelling procedure for a virtual PID

Antecedent	Consequent
IF $e = A_1$	THEN $u_1 = K_p*A_1$
IF $\Sigma e = A_2$	THEN $u_2 = K_d*A_2$
IF $\Delta e = A_3$	THEN $u_3 = K_i*A_3$

Table 3: The consequence of the additive property

Antecedent
IF $e = A_1$ AND
IF $\Sigma e = A_2$ AND
IF $\Delta e = A_3$
Consequent
THEN $U = K_p*A_1 + K_d*A_2 + K_i*A_3$

which can be expressed in standard rule format as

IF e is A_1 **AND** Σe is A_2 **AND** Δe is A_3
THEN $U = K_p*A_1 + K_i*A_2 + K_d*A_3$

3 SIMULATION RESULTS AND CONCLUSIONS

Experimental results has been obtained by simulating a process model. A model of the motion of a standard marine vehicle has been used. Figure 5 shows typical excitation and response signals obtained when designing the virtual controller by the Harmonic Balance design method. Figure 6 shows the three rule bases of the final fuzzy controller. These rule bases are used in additive mode to get a crisp output. Figure 7 shows the time response of the fuzzy controller. It is using only a reduced number of rules (13 rules).

As conclusion, it has been showed that the fuzzy reasoning procedure adopted first by Takagi&Sugeno is a proper method to get a fuzzy rule base with reduced number of rules. The advantage of having this reduced rule base is that it could be easily modified and adjusted by a plant operator acting only in one or more premises (i.e. the proportional action, the derivative action, etc.) with total independence. Besides that, the simplicity of the method guarantees that it could be implemented in a IEC compliant PLC without any additional fuzzy-oriented hardware or software.

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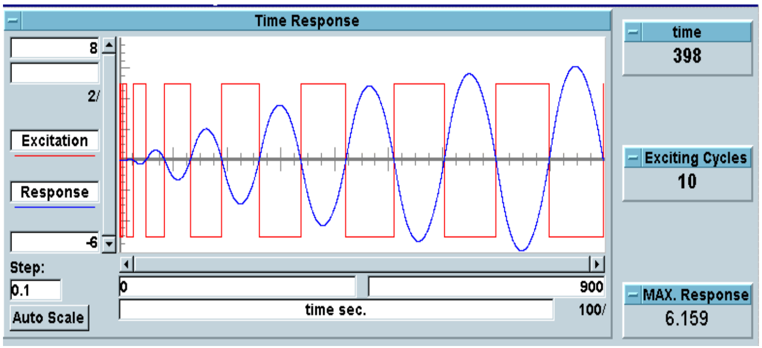

Figure 5: Virtual controller design by Harmonic Balance method

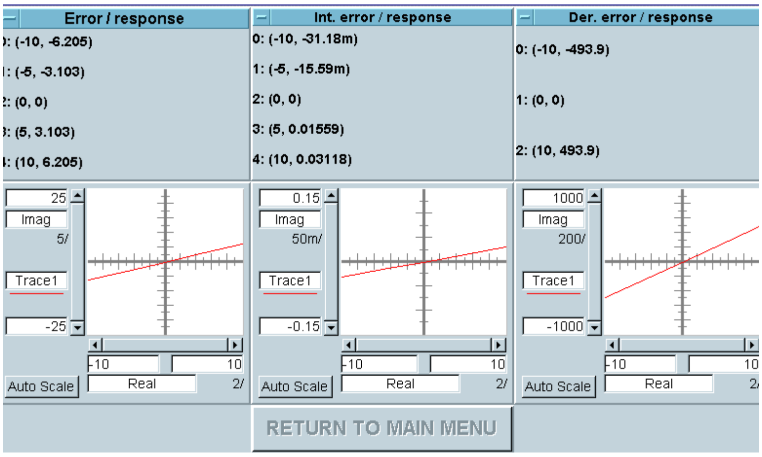

Figure 6: Fuzzy controller rule-base (13rules)

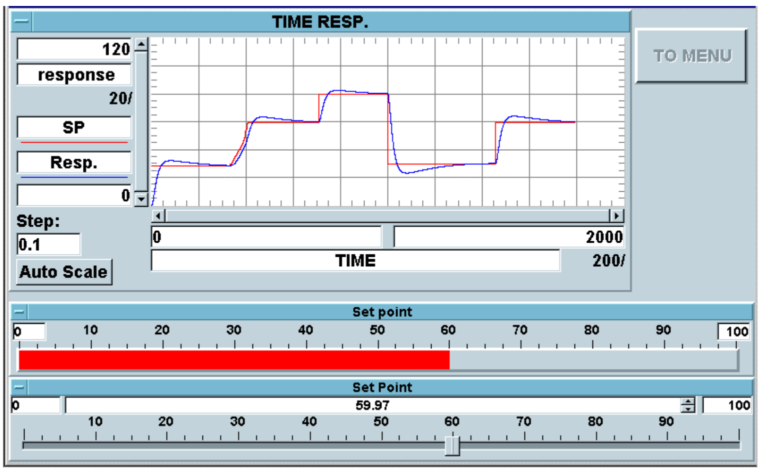

Figure 7: Time response of the fuzzy controller