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THE IDENTIFICATION OF THE OPERATING REGIMES OF THE CONTROLLERS BY THE HELP OF THE PHASE TRAJECTORY

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Abstract

The paper presents an on-line identification method of the operating regimes of the closed loop con-trollers. This method uses as main tool the phase trajectory of the control error, which is analysed in a qualitative manner. The operating domain is divided into four regimes: variable, steady, oscillating and unstable. This operation may be performed by fuzzy or by interpolative controllers, on the base of general knowledge on the PID controllers adjustment. A high quality self-adaptation of the controllers may thus be obtained, covering all the possible operation regimes.

Keywords: *fuzzy interpolative controllers, adaptive control, phase trajectory, heuristic control rules.*

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1. INTRODUCTION

The control of the non-linear and time variable plants demands a high quality self-adaptation, covering a wide range of possible combinations of the parameters of the system. A conventional control fails when it has to deal with contradictory clauses. For instance the integrative effect of the PID controller may produce notable overshoots and oscillations during the vari-able regimes but in the same time its help is welcome during the steady ones. The adjustment of a dc drive controller for ordinary speeds does not matches at low speeds, because of to the non-linearity of the friction load torque, which is growing when the speed is decreasing.
However these contradictions may be managed by the help of the fusion of several controllers each one designed for a specific operating regime. The fuzzy fusion of the controllers became in the last years a reliable solution to this problem.
The goal of this lesson is to offer a simple and reliable method for the on-line identification of each regime that could possible produce contradictions when adjusting a PID basic controller. The lesson is based on a previous paper [8].

2. THE BASIC ASSUMPTIONS

The first question that comes in our mind when dealing with barely controllable plants (highly nonlinear, death time, mathematically unknown, etc.) is: "how would a human operator control this plant?" Many specialists may disregard this heuristic approach, but still it has fundamental advantages over the numerical algorithms: it can always be applied! Of course the performances may be not optimal, and a rigorous solution to the stability problem is not possible, but in turn the costs of the development of new products is getting lower and special applicative measures against instability can always be considered. And nevertheless, the accumulation of experimental facts about the heuristic controlled systems is a basic condition for the developing of further numerical algorithms.

The basic assumptions that we will take in account are the next ones:

- The PID is the fundamental control algorithm since, in a general way of speaking, it can handle the present (P), the history (I) and the future (D) of the evolution of the system. The expert knowledge of the PID adjustment offers reliable control rules for the most part of the possible control applications.
- The self-adaptation is strictly necessary for highly nonlinear and/or time variable plants.
- A very attractive adaptation tool for the on-line control is the 2D phase trajectory of the control error $\dot{\boldsymbol{\varepsilon}} = f(\boldsymbol{\varepsilon})$ (the dependence between the change of error $\dot{\boldsymbol{\varepsilon}}$ and the error $\boldsymbol{\varepsilon}$). The phase trajectory of the error is a fundamental tool, which has a significant weight in the elaboration of the control decisions by the human operators.
- The adaptive strategy will be a heuristic one, the only one that is able to cope with the highly nonlinear systems.
- The fuzzy logic is a basic tool that allows us to cope with the specific incertitude of the complicated nonlinear systems and with the qualitative or heuristic approaches [6], [7].
- The fuzzy fusion of the controllers or only of the adaptive part of the controllers is necessary for the management of the contradictions.
- The fuzzy controllers may be developed by a linguistic method. In order to obtain reliable implementations we will use only fuzzy controllers that have a linear interpolation correspondent (so called fuzzy-interpolative controllers). The prod-sum Sugeno fuzzy inference and COG defuzzyfication is an obvious first choice [3].

3. THE *FFSAIC* ADAPTIVE CONTROLLERS

Any fuzzy controller is an interpolative one as well, and may be implemented by means of a look-up table with linear interpolation (similar to the Matlab-Simulink look-up table). Such an implementation may be considered as a *fuzzy interpolative controller* [3]. The main advantage of this kind of structures consists in the easiness of the implementations (both software or hardware). Interpolative controllers are able to perform quite similarly to any other kind of controllers having in the mean time the advantage of a low amount of calculations and of the speed [4], [5]. The electronic implementations are feasible in any possible technology, even in the analogical ones, since the only important mathematic operation involved is the linear interpolation.

Yet the look-up tables are strictly numerical tools, their representation in the human mind being inadequate, especially when using large or multidimensional tables. Thus the fuzzy feature becomes useful mainly for methodological reasons. The linguistic representation of the knowledge is revelatory for humans, catalysing the developing stages of the applications. The fuzzy controllers used in this paper will be fuzzy-interpolative, and by consequence they will be implemented by look-up tables.

We will consider as a recommendable tool a specific controller structure which is operating by analysing the phase trajectory of the error and which was designed having in mind the previous assumptions. This structure will be called FSAIC (*Fuzzy Self-Adapted Interpolative Controller*) [3] and it is shown in Fig.1.

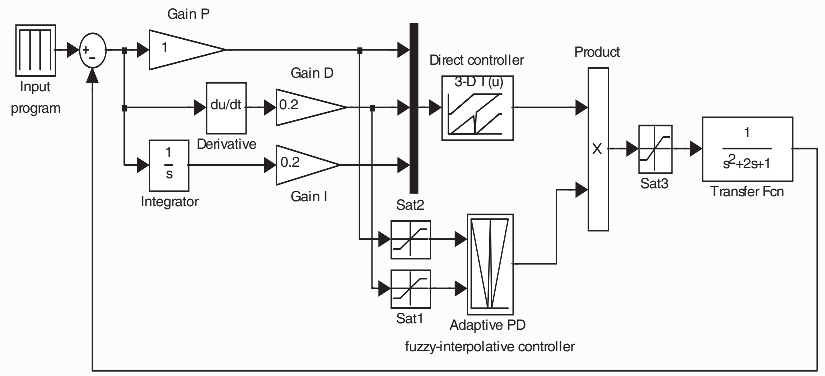

Fig. 1. A FSAIC controller

The characteristic features of this structure are the following:

● *FSAIC has a variable structure*. During transient regimes the main controller is a PD one. During the steady regime an integrative effect is gradually introduced, the structure becoming a PID one. This functionality may be achieved with a 3D look-up table having as inputs **ε**, $\dot{\boldsymbol{\varepsilon}}$ and **∫ε**, the integrative of the error. The different PD tables corresponding to the **∫ε** dimension differ only at the central rule, that is activated when **ε = zero** and $\dot{\boldsymbol{\varepsilon}}$ **= zero** [1], [2], [3]. Thus the integrative effect is gradually activated, through a linear interpolation, only when steady regimes occur. The block that fulfils this functionality in Fig. 1 is Direct controller.

● *A fuzzy-interpolative PD controller (corrector) induces the adaptive feature*. The adaptive controller is generating a multiplying correction (*Gain*) over the output of the main controller; the multiplying correction is preferable to the additive one by allowing a direct fuzzy fusion. The PD structure is chosen because it can be matched with the phase trajectory of the error (see Table 1, next page). The corresponding block in Fig. 1 is Adaptive PD fuzzy-interpolative controller.

In the following paragraphs we will focus on the adaptive correction. The adaptive control rules could be grouped into four clusters according to the next classification of the main operating regimes: variable (G1), steady (G2), oscillating (G3) and unstable (G4). This point of view is not the only possible, other classifications being as well productive. The clusters of rules must respect in great shapes the next linguistic commitments:

- G1: < *Gain* is **medium** and *Integrative* is **zero** >
- G2: < *Gain* is **great** and *Integrative* is **great** >
  (1)
- G3 & G4: < *Gain* is **small** and *Integrative* is **zero** >

The *Integrative* variable is generated by Direct controller.
The differences between G3 and G4 are not fundamental. If necessary they may be separated by the help of supplementary criteria, for example with the help of the product of the first and second derivatives of the control error, that is positive for unstable systems [3]. Anyway, *Gain* must be reduced in order to reject the oscillations and/or to stabilize the system, in the sense of the Nyquist stability criterion. Due to the non-linearity of the plant, an optimal crisp value of the *Gain* would have no sense.
In the next table a possible structure of adaptive PD fuzzy-interpolative corrector is presented.

Table 1: An adaptive PD fuzzy-interpolative controller

$\dot{\varepsilon}$

change of error $\dot{\varepsilon}$ / error ε	negative	zero	positive
positive big	G1	G1	G1
positive small	G3	G3	G3
zero	G1	G2	G1
negative small	G3	G3	G3
negative big	G1	G1	G1

ε

A typical phase trajectory of the error is underlying its the correspondence with the table.

4. THE FUZZY FUSION OF THE ADAPTIVE CORRECTORS

When the blending of the rules is not possible or satisfactory, the fundamental solution is the fuzzy fusion of the individual controllers. The simplest fuzzy fusion operates according to the weighted sum formula:

$$u(t) = \frac{\sum_i \mu_i(t) \cdot u_i(t)}{\sum_i \mu_i(t)} \tag{2}$$

where u_i is the output of the controller i and μ_i is the membership value of the same controller. More complicated shapes for the membership values functions may be used when imposed performances must be reached.

A *Fusioned Fuzzy Self-Adapted Interpolative Controller* (FFSAIC) is presented in Fig. 2.

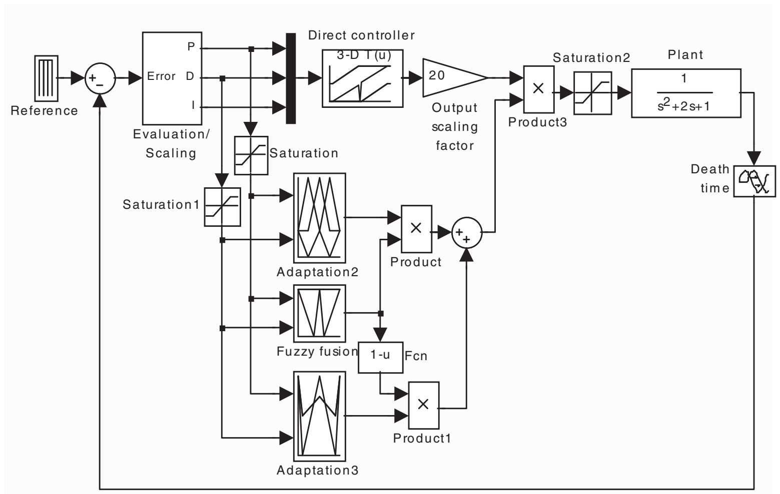

Fig. 2. A FFSAIC controller

FFSAIC may include several different PD adaptive controllers (correctors), each one dedica-ted to a specific operating regime. In Fig. 2 a minimum FFSAIC variant is presented, having only two correctors, corresponding to the regimes G1&G2 (which may be covered by the same adaptive corrector) and G3. The Table 2 controller may be applied in order to control the fuzzy fusion of three correctors. The heuristic meanings of the identifications of G1 and G3 are obvious, while the identification of G3 (oscillations) is linked to the points $\dot{\boldsymbol{\varepsilon}} = \mathbf{0}$: if the error is **zero** (in the linguistic sense) the regime is steady, if not, the regime is oscillatory.

Table 2: A regime identification fuzzy-interpolative controller

change of error $\dot{\varepsilon}$ / error ε	negative	zero	positive
positive big	G1	G1	G1
positive small	G1	G3	G1
zero	G1	G2	G1
negative small	G1	G3	G1
negative big	G1	G1	G1

5 COMPARING *FSAIC* TO LINEAR *PID*. SIMULATIONS RESULTS

The next examples have only an illustrative goal. Some detailed results may be found in [3].

Fig. 3 presents a comparison of FSAIC and linear PID performances for the case of an oscillatory plant, with the transfer function

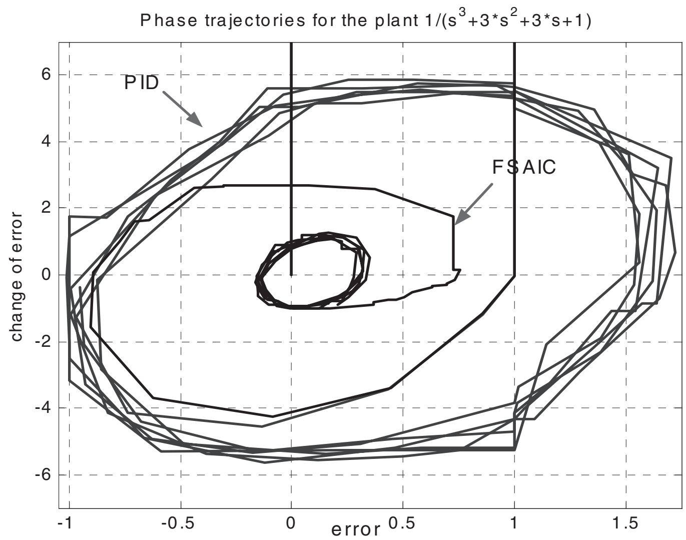

Fig. 3.The performance of FSAIC comparing to PID

$$H(s) = \frac{1}{s^3 + 3 \cdot s^2 + 3 \cdot s + 1} \quad (3)$$

Fig. 4 presents the time performances of FFSAIC when controlling four different plants:

$$H_1(s) = \frac{1}{s^2 + 2 \cdot s + 1} \quad (4)$$

$$H_2(s) = \frac{e^{-0.025s}}{s^2 + 0.2 \cdot s + 1} \quad (5)$$

$$H_3(s) = \frac{e^{-0.025s}}{s^2 + 20 \cdot s + 1} \quad (6)$$

$$H_4(s) = \frac{e^{-0.025s}}{s^3 + 3 \cdot s^2 + 3 \cdot s + 1} \quad (7)$$

If linear PID controllers would control them, the tested plants would produce extremely different responses, one of them being fully unstable.

6 CONCLUSIONS

The identification of the operating regime of the closed loop control systems may be obtained by the means of the *qualitative* analyse of the phase trajectory of the control error. Adaptive actions based on this approach are able to improve the control of highly nonlinear and/or important dead times plants.

This analysis may be achieved with the help of fuzzy-interpolative controllers. A family of fuzzy self-adaptive interpolative controllers FSAIC is designed to implement this kind of operation. The adaptive part of FSAIC is a fuzzy-interpolative PD corrector.

The regime identification may ensure a high quality adaptation even in the case of contradictory clauses. The tool that can cope with the contradictory possible regimes (FFSAIC) is obtained by the fuzzy fusion of several adapting FSAIC correcting controllers. The on-line control of the fuzzy fusion is achieved as well by a fuzzy-interpolative controller.

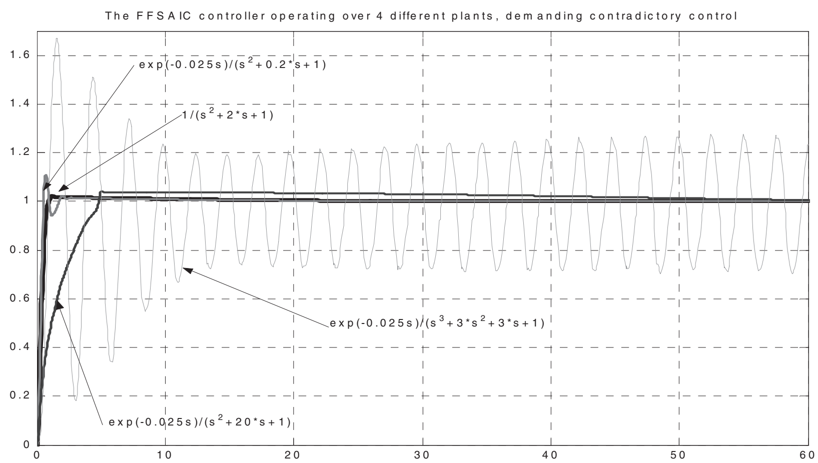

Fig. 4. Tne FFSAIC with the on-line identification of the operating regime

FFSAIC can also control systems that are suffering unstabilising influences.

Only two possible applications of FSAIC are revealed so far: the air-conditioning [1] and the ABS braking [2] of the railway coaches. Further research could produce important applicative achievements, since the method is a versatile and easy to implement one.

REFERENCES:

[1] Bălaş M., The temperature control by variable structure interpolative PID controllers. *Proceedings of the 6th International Conference on Engineering of Modern Electric Systems*. University of Oradea, May, 2001.

[2] Bălaş M., Bălaş V., Foulloy L., Galichet S., A model of the sliding wheel during braking. *Proceedings of the 5th International Conference on Railway Bogies and Running Gears BOGIE'01*, Budapest, Sept., 2001.

[3] Bălaş M., Regulatoare fuzzy interpolative, Politehnica Timişoara, 2002.

[4] Dragomir T.L., Interpolative Controllers – a Correctional and Improvement Alternative for Design and Implementation. *Proceedings of the 6th International Conference on Engineering of Modern Electric Systems EMES'01*, Oradea, May, 2001.

[5] Dragomir T.L., Dale S., Bălaş M., Some aspects regarding interpolative control. *The 13th International Conference on Control Systems, CSCS13*, Bucureşti, Nov. 2001.

[6] Foulloy L., Qualitative Control and Fuzzy Control: Towards a Writing Methodology, *AICOM* Vol. 6, Nrs. 3/4 Sept./Dec., pag. 147-154, 1993.

[7] Stoll K.E., Ralston P.A.S., Ward T.L., Linguistic Design of Nonlinear Controllers. *Journal of Intelligent and Fuzzy Systems*, vol. 4, nr.1, 19-32, 1996.

[8] M. Bălaş, V. Bălaş, T.L. Dragomir, „A Preamble on the Identification of the Operating Regimes of the Controllers by the Help of the Phase Trajectory", Electronic BUSEFAL nr. 87, June 2002, http://www.univ-savoie.fr/ Portail/ Groupes/ LISTIC/ busefal/ Papers/ 87.zip/ 87_01