Fifth IFSA World Congress (1993), 814-817

Fuzzy Controller : Design, Evaluation, Parallel and Hierarchical Combination with a PID Controller

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Abstract—
Fuzzy controllers still remain ill-accepted in the control community. As a matter of fact, their design relies on a new relation between the material world and the scientists. Whereas some theoritical studies are carried out on this subject, experimentations on processes show what fuzzy techniques can bring to the control theory.

I. INTRODUCTION

The goal of the present work is to evaluate the advantages of using combinations of non-conventional and conventional control techniques by using them on different plants (an industrial furnace and a D.C. motor). Fuzzy control techniques are considered here in order to build different kind of structures. These techniques have some interesting potentiality, which can be used to enhance the qualities of P.I.D. controllers. The structures proposed are direct fuzzy controller, a parallel structure and a hierarchical structure using both P.I.D. and fuzzy controller. For each of these control algorithms, properties and improvements compared with P.I.D. control are emphasized.

II. FUZZY CONTROLLER : TWO DIFFERENT CONTROL STRATEGIES

A. *Fuzzy controller*

1) Structure and design: The fuzzy controller computes values of either the control signal or the control increment signal as a function of the values of the output error and its change. First of all, a quantization module discretizes and normalizes the universe of discourse of the various manipulated variables. Then, a numerical-fuzzy converter maps crisp data to fuzzy numbers characterised by a fuzzy set and a linguistic label; the inference engine applies the compositional rule of inference to the rule base in order to derive fuzzy values of the control signal from the input facts of the controller. Finally, a fuzzy-numerical converter and a dequantization module provide a numerical value of the control signal that is applied to the process, see [LEE,90] for an exhaustive synthesis about the direct fuzzy controllers. The method developed in this work to derive the fuzzy rules is heuristic. The desired closed-loop trajectory is observed in the phase plane or in the time domain. The dynamic response is divided into several regions, each of which corresponds to a specific pair composed of error and change of error fuzzy values. Each pair is mapped to the necessary fuzzy value of the control signal that will make the dynamic response converge towards the desired trajectory. This mapping leads to the definition of a linguistic phase plane. The control strategy used consists of using a coarse tuning during the transient and a fine tuning during the steady-state. Each kind of tuning procedure is characterized by a look-up table that links the quantized and normalized values of the three considered signals. In some cases a special control strategy is used. This strategy consists of using a fuzzy gain on the control increment values in order to compensate the various numerical approximations performed during the fuzzy controller computing.

2) Simulations, comparison with a PID controller: Two different experiments in simulation and in real time have been performed on the approach described before. The first experiment is the control of the speed of a motor-alternator group. The process is modelled by a first order system with a static gain of 23.6 and a time constant of 3 s. The change in the motor load play the role of disturbances. The tuned fuzzy controller has been used in simulation and in real time. The experimental studies with the motor aim at observing the influence of the definition of the actual universe of discourse of the control increment gain on the quality of the control. The figure (2) shows some results for two different universes of discourse of the gain G (where ^{C} denotes *coarse* and ^{F} *fine*). The results obtained with the motor emphasize that the rise time is improved where as the overshoot increase when the bound of the actual universe of discourses is increasing. The figure (3) shows the result of the motor control in real time. The results are similar to those obtained in simulation. The rise time is small, about 150 ms. Oscillations appear in steady state when the motor has no load, this phenomenon is caused by the mechanical disturbances of the axe.

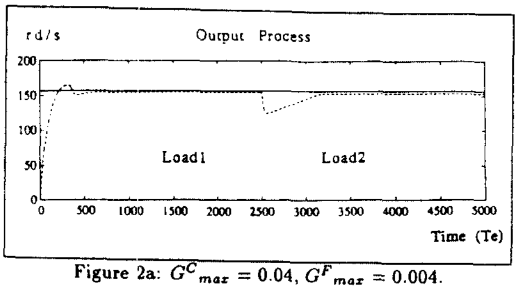

Figure 2a: $G^C_{max} = 0.04$, $G^F_{max} = 0.004$.

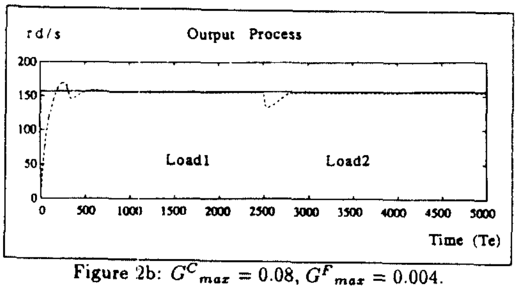

Figure 2b: $G^C_{max} = 0.08$, $G^F_{max} = 0.004$.

Fig. 2. Influence of the gain universe of discourse.

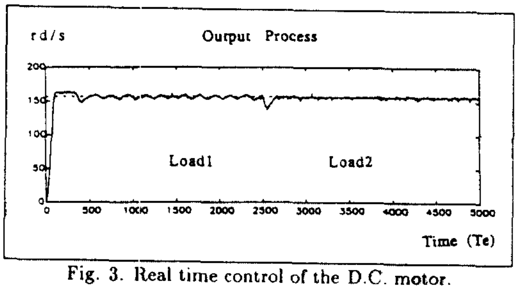

Fig. 3. Real time control of the D.C. motor.

The second group of experiments are concerned with the control of the temperature of industrial furnaces. The models of equation (1) are considered. A comparative study between a PID and a fuzzy regulation of the furnace is performed for different static gain, G_f, in order to test the robustness of the two type of controllers. The figure (5) show the simulation results. The results obtained with the furnace lead to the following conclusions. Firstly, both controllers are able to handle the gain disturbances; secondly, during the steady-state, some oscillations appear with the fuzzy controller; and thirdly, during the transients, at the beginning of a step change or after a perturbation, the fuzzy controller is quicker to converge to the setpoint than the P.I.D. controller.

$$\begin{cases} G(p) = \frac{G_f}{1+T_e.p} \\ G(p) = \frac{G_f exp^{-T_e.p}}{(1+T_e.p)^2} \end{cases} \qquad (1)$$

The results show the ability of the fuzzy controller to improve the closed-loop performances during the transient. Nevertheless, during the steady-state, only the PID controller can give no steady-state error by means of the reset time constant.

B. *Parallel control structure with a P.I.D. and a fuzzy controller*

A first idea to combine conventional and non-conventional control techniques consists of building a parallel structure. According to the current dynamic state, either the PID or the fuzzy controller is selected. The fine tuning of the fuzzy controller is somewhat replaced by the PID regulation. The main point during the design of this type of control structure is the determination of the commutation logic. For this purpose, an additional fuzzy variable is defined. A set of fuzzy rules express the commutation strategy, that is the definition of the state of the fuzzy commutation variable in terms of the error and the change of error values. The method developed is based on the following definition of the transient : the product of the error and its change is negative. When the change of error value is equal to the fuzzy value 'ZERO' and the steady state error is small then the PID controller is selected. By that way, a lot of commutations between the two controllers are avoided. The resulting behaviour in the phase plane is illustrated in figure (6).

The experiments are made with the motor-alternator group. The load is varying during the simulation in order to introduce some internal perturbations. The PID is tuned with the Ziegler & Nichols algorithm. We use the same fuzzy controller as described before. The results are shown in figure (7). The reached performances are : a rise time of 150 ms for the parallel control structure and 225 ms for the PID controller. The fuzzy controller is used during all the transients. The parallel control structure proposed is effectively able to combine the rapidity of the fuzzy controller during the transient with the accuracy of the PID controller during the steady-state.

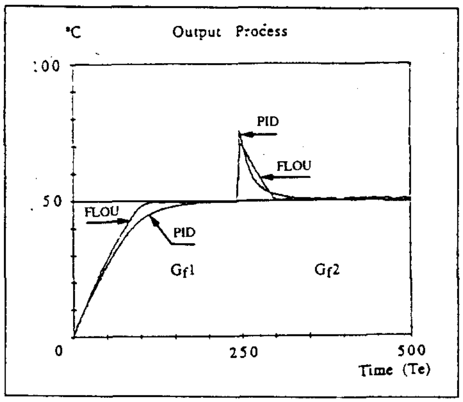

Figure 5a: First order model, $G_f = G_0$ and $G_f = 2 \times G_0$.

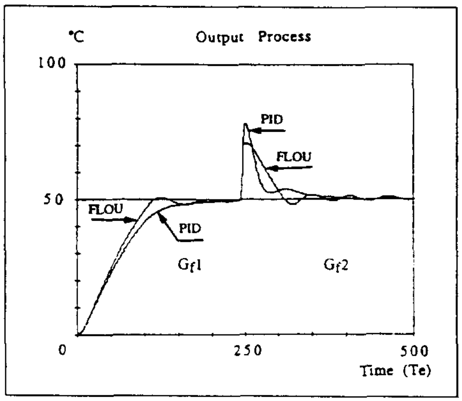

Figure 5b: Second order model, $G_f = G_0$ and $G_f = 2 \times G_0$.

Fig. 5. Comparison of fuzzy and P.I.D. controllers on the two furnace models for different static gain.

$e \downarrow \Delta e \rightarrow$	NB	NM	NS	ZE	PS	PM	PB
NB	PID	PID	PID	F	F	F	F
NM	PID	PID	PID	F	F	F	F
NS	PID	PID	PID	PID	F	F	F
ZE	PID	PID	PID	PID	PID	PID	PID
PS	F	F	F	PID	PID	PID	PID
PM	F	F	F	F	PID	PID	PID
PB	F	F	F	F	PID	PID	PID

Fig. 6. The commutation logic, (F = Fuzzy).

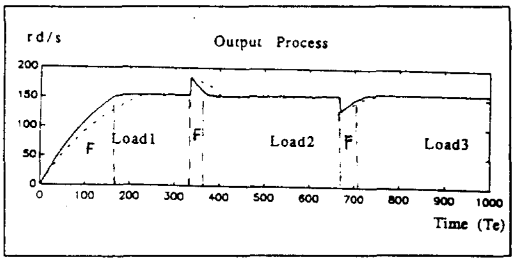

Fig. 7. Control of the D.C. motor speed with the parallel fuzzy-P.I.D. controller.

III. FUZZY SUPERVISION OF A PID CONTROLLER

A. Fuzzy supervisors : justification, structure

The problem of the precise determination of the commutation point between PID and fuzzy controllers is not straight forward. Then, another kind of combination of conventional and non-conventional techniques is considered. A hierarchical structure is built in order to supervise the control loop and to tune the PID parameters. There are several reasons for supervising a PID controller. The main one is that in many industrial applications of control engineering, PID controllers have already been installed. This controller is robust in low perturbated situations but becomes under-optimal when large variations of some regulation loop parameters occur. Consequently, the goal of the supervisor is to improve the abilities of the PID controllers to control optimally systems in highly perturbated context according to the user's wishes.

The internal structure of the supervisor is the same as the one of a fuzzy controller. The outputs of the supervisor are the changes to be applied to the PID parameters. The supervisor inputs are the performance values reached after a transient. The measure of the regulation quality during a time interval allows to compute the adaptation of the control law for the future, see [LIT,91] for an example of this kind of fuzzy supervision of P.I.D. controllers . The values of the rise time, overshoot and stability factor are used to tune the PID gains. The stability factor is the ratio of the first undershoot to the first overshoot. The main supervisor parameters to be tuned are the scaling factors of the universes of discourse and the fuzzy rules. Some stability analyses give the limit values of the different manipulated signals. These limit values are used to define the bound of the actual universe of discourse of the variables. In the case of the supervisor's input variables, these bounds are also determined by the desired values of the dynamic features. The supervision law translates the fact that the control law has to be in a state such that the dynamic response converges towards a model response. This reference trajectory is characterised by some medium fuzzy values of the performance characteristics. In the first stage some transient responses are obtained in order to evaluate the influence of each PID parameter. A linguistic model connecting the fuzzy values of the PID parameters to the fuzzy values of the performance characteristics is built. In the second stage, some tuning tables are derived. They express the adjustments to be applied to each PID parameters separately in order to make the dynamic characteristics converge to their mean value. The last stage consists of deriving the fuzzy tuning action to be performed independently on each controller gain so that the dynamic response converges to the reference response. Three look up tables are then computed. Each table adapts one of the PID controller gains.

B. results

The experiment is carried out on the motor-alternator group that simulates a good example of perturbated environment. The PID parameters are initialized with the Ziegler & Nichols method. The desired dynamic response has the following characteristics : a rise time of 36 ms, an overshoot of 0.2 and a stability factor of 750. The reference signal is changing in order to evaluate the PID parameters tuning ability of the supervisor during the transients and the regulation quality during the steady-states. Two simulations are performed; during the first one the P and I parameters are tuned, whereas in the second one no adaptation of the PID gains is performed. The figure (8) shows the results. In the first case the rise time is equal to 36 ms, the overshoot to 0.2 and the stability factor to 750. When no P.I.D. gains adaptation is done, the rise time is 48 ms and the overshoot is 3 for the worst transient. The results obtained with the fuzzy supervisor show that the specifications can be achieved. The comparison between a PID and a supervised PID regulation points out the advantage of using a fuzzy supervisor. The overshoot and oscillations are strongly decreased. This improvement is due principally to the adaptation of the integral gain. Indeed, the supervision rules express the fact that the overshoot is very sensitive to the integral gain changes. The rise time is above all sensitive to the proportional gain changes.

Therefore, the results of the simulation show some interesting aspects of fuzzy supervision of PID controllers.

IV. CONCLUSIONS AND PERSPECTIVES

In the present work fuzzy logic has been used in different control structures, in direct control or supervision. The comparison between fuzzy control and P.I.D. control emphasize the facts that the fuzzy controller is more interesting for the transient response, however it can be worse during the steady state. That is the reason why a parallel control structure combining a P.I.D. and a fuzzy controller has been build. In the last structure considered, the fuzzy logic is used for supervision. It has been possible to obtain some interesting results. The obtained results emphasize the fact that fuzzy techniques can be used to enhance conventional control methods, even though specific points have to be examined further.

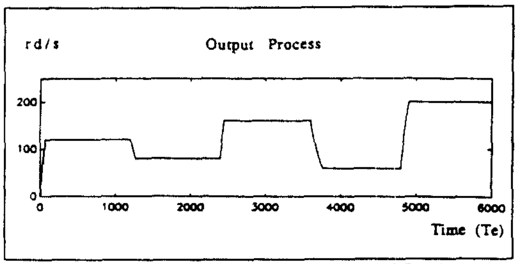

Fig. 8a. Fuzzy supervision of the P and I gains.

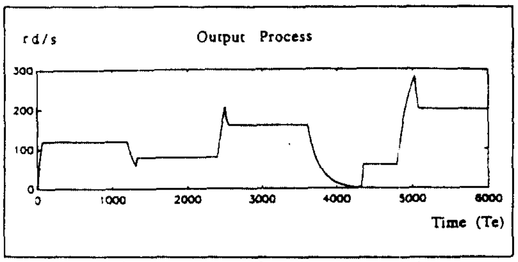

Fig. 8b. P.I.D. control without supervision.

Fig. 8. Control of the D.C. motor speed.

REFERENCES

[LEE,90] Lee, C. C., "Fuzzy Logic in Control Systems: Fuzzy Logic Controller - Part 1 and ", IEEE Transactions on Systems, Man, and Cybernetics, vol. 20, No 2, March/April 1990, pp. 404-435.

[LIT,91] Litt, J., "An Expert System to Perform On-line Controller Tuning", IEEE Control Systems, 1991, April, pp. 18-23.