Composite Fuzzy-Conventional Control Applied To Earth Pressure Balanced Shield Front Pressure Stabilization

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Abstract: This paper presents the so-called composite fuzzy-conventional control. Fuzzy control is combined with a traditional P.I.D. control which applied to a process compensates the closed-loop error. Tuning parameters are shown to be easy to tune. Application to a complex and multivariable system is developed, in an industrial environment.

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1. Introduction

The number of applications of fuzzy control has slightly increased since the first attempts to use it. Japanese industry particularly led that method to a well-known success. What does nevertheless remain a problem is the lack of conditions ensuring stability or performance and the fact that closed-loop traditional control knowledge which is not so bad! - is not used.

Very often too, rules and membership functions tuning takes a long time and is not easy to execute for a non-specialist. Generally speaking, fuzzy control is applied to an open-loop process; the so-called composite fuzzy-conventional control is simply the composition of a fuzzy control and a conventional control; in this case, a fuzzy controller is applied to an already P.I.D. tuned closed-loop process.

Rules are using closed-loop error, so that a certain stability has already been obtained with P.I.D. control and so that performance should be obtained by reducing closed-loop error with fuzzy control.

Such a control proves to be

- quite robust in respect to its own parameters;
- robust in respect to plant parameters variations;
- easy to implement.

All these features are developed in part I.

In the particular case studied, in part II, a highly complex system is controlled with composite fuzzy-conventional control. The main features of the system are:

- non- linearity;
- time-varying parameters;
- parameter uncertainty (difficult identification);
- important external disturbances;
- multivariable;
- actuators saturation;
- severe industrial environment (noise, vibrations, dust...as in any underground work).

Any model-based control could not suit such a system. Anyway, our control, with a limited number of rules determined by experience and common sense, is able to cope with variations and to regulate the process.

2. Composite Fuzzy-Conventional Control

A. Fuzzy Control

Fuzzy logic has been introduced by Zadeh [1] in which a fuzzy subset E defined in a discourse universe U is defined by a membership function μE which takes its value in [0, 1]:

$$\mu E \quad U \rightarrow [0,1]$$
$$u \rightarrow \mu E$$

Fuzzy control represents expert fuzzy rules of the type: if E is A and CE is B then CO is C, in which E is the process output error, CE- variation of E, CO-change of Control and A, B, C-fuzzy predicates.

The Sugeno [2] method consists in applying the following inference rule: If X is A then Y is B; if X has a crisp value X_0, Y takes its value in the fuzzy subset V in which the predicate B is defined, the membership function of predicate A is μ_A and the membership function of predicate B is μ_B; The membership function of the output will then be $\mu'_B(Y) = \min\left(\mu_A\left(X_0\right), \mu_B(Y)\right)$. That will be our inference method to design our controller.

Several other methods exist; the purpose of this paper is not to make the advantages of different methods explicit.

A fuzzy controller will thus be composed of 5 main elements [2]:

- a database of fuzzy subsets;
- a database of rules;
- a fuzzification interface which allows transformation of crisp values into fuzzy values;
- a defuzzification interface transforming fuzzy control into crisp control;
- a calculus module which determines fuzzy control with the defined inference method.

As our fuzzy controller can be very simple, membership functions will be affine, inference method being Sugenos'. The robustness of such controllers is often obtained at the expense of performances [3].

B. Composite Fuzzy-Conventional Control

Generally speaking, a Composite Fuzzy-Conventional control is a composition of fuzzy and conventional control applied to the same control loop; if the model of the process is defined by $\frac{df(x)}{dt} = f(x) + g(u)$ and the control by $u = p(x)$, then the fuzzy control is u_f in which $u_f = f(p,u)$.

This relation is represented by the scheme below:

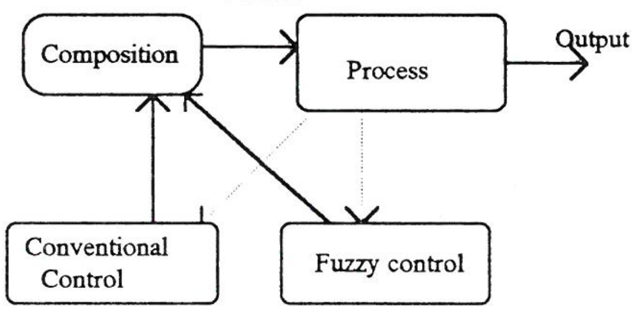

Figure 1. Composite Fuzzy-Conventional Control

In our application, such an algorithm is represented by the scheme below.

This simply means that the closed-loop process is tuned by a fuzzy controller that increases performances.

Applications are shown to be good for a first-order process with a wrong model.

P.I.D. parameters themselves also exist: but those parameters are not difficult to tune as they only need render the process stable.

Rules then only need be simple and a single look up-table is needed as the control designer just works on small quantities, that is to say an already small control error. Rules are therefore simpler

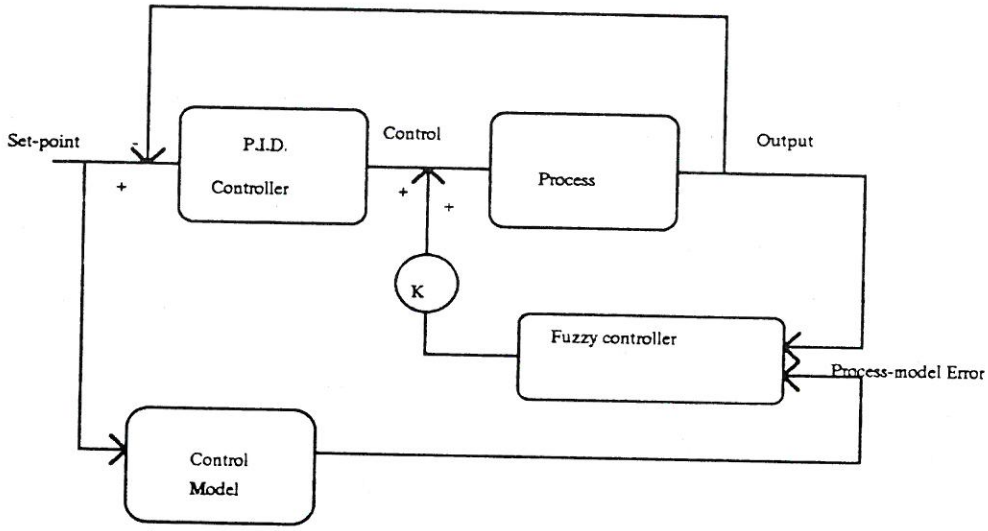

Figure 2. Composite Fuzzy-P.I.D. Control

than in fuzzy control alone, where they need be exhaustive.

3. Application to Tunnelling Process

Trenchless methods are used today for digging in urban areas; ground settlements are of course one of the main problems faced by contractors.

Earth Pressure Balanced Shields such as the ones built by FCB company are particularly fit for this kind of a job: these machines are constituted of a cutter disk rotating and taking the soil out, and an evacuation system for excavated ground. A necessary pressure equilibrium between the machine and the soil is created by confining ground into a chamber under pressure.

Excavated ground is evacuated with a screw conveyor, which characterizes EPBS concept. The great difficulty is that excavation and extraction speeds are difficult to anticipate as ground properties are always changing.

Earth pressure sensors situated on the head of the machine give a measure of the pressure at the cutting front. Front pressure - called earth pressure - is often controlled with screw speed.

However, tunnelling speed is also important for the front pressure. Some problems occur when starting a stroke as torque overshooting is not allowed and pressure gets slightly higher at the front of the machine.

The following drawing explains how the machine works:

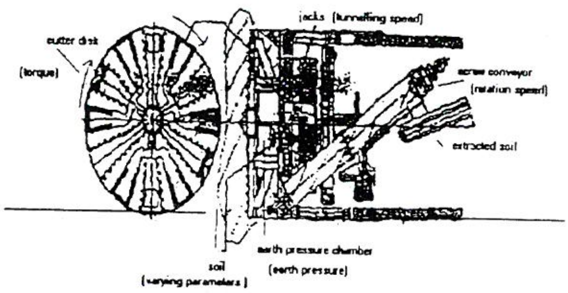

Figure 3. EPBS Machine

The control problem can be summarized as

- maintaining front pressure around set-point- ±0.05 bars (main goal);
- tunnelling speed optimization;

Constraints :

- the torque is to be maintained beneath a given value;

- the impossibility of acting on disc speed (disc speed is not an actuator but it has an influence on torque and pressure);
- actuator saturation;
- constraints on machine operating conditions.

Fuzzy control has already been implemented on tunnelling machines, see for instance [5]. But, in practice, the control pilot often takes the machine back in manual mode when a problem occurs, when pressure gets up or down. On beginning the work, parameters are particularly difficult to tune, inducing an important delay for the contractor.

After a quick identification, we can describe the tunnelling process with the following relations:

$$\begin{pmatrix} T(p) \\ P(p) \end{pmatrix} = \begin{pmatrix} 0 & H_{12}(p) & H_{13}(p) \\ H_{21}(p) & H_{22}(p) & H_{23}(p) \end{pmatrix} \begin{pmatrix} S_{sc}(p) \\ S_t(p) \\ S_d(p) \end{pmatrix}$$

T is disc torque T.m

P is front pressure in bars

S_{sc} is screw conveyor rotation speed in r.p.m

S_t is tunnelling speed in mm/mn

S_d is disc speed in r.p.m.

H_{12} is a first order, H_{13} a second order, H_{21} and H_{22} first orders with integrator, H_{23} an oscillator.

The model is sampled with a period of 1 second for the pressure loop and 10 seconds for the torque loop.

This identification has been made, in practice, by the acquisition of the concerned values and by Strejc methods confirmed by RLS identification to get better parameters. As ground parameters are changing, parameters' uncertainty generally figures 20%, or sometimes more.

On our two control loops, a Composite controller is designed; there are only a few rules, for pressure-screw rotating speed loop:

- if set-point model-pressure error is negative, lower screw conveyor speed;
- if set-point model-pressure error is positive, increase screw conveyor speed;
- if set-point model-pressure error is zero and error change increases, increase screw conveyor speed;
- if set-point model-pressure error is zero and error change is negative, lower screw conveyor speed;
- if set-point model-pressure error is zero and error change is zero, maintain conveyor speed;

and for torque-tunnelling speed loop:

- if set-point model-torque error is negative and (pressure is not high or error change is negative), increase EPBS speed;
- if set-point model-torque error is positive, lower EPBS speed.

Determination of fuzzy membership functions is achieved by experience: for instance, the EPBS operators let the control strategy work by itself when the pressure is between ±0.05 bars around the set-point, which gives the limits of the membership function "pressure is medium", and will drive the machine in manual mode when the pressure is over 1.6 bars, which gives a limit to the membership function "pressure is high".

It is about the same with tunnelling speed: if the torque is too high, that is to say, over the limit value, then we have the limit for "high tunnelling speed". A low tunnelling speed is a tunnelling speed with a torque more than 20% under the authorized limit.

The shape of membership functions is affine; defuzzification is achieved by centroid method, that is to say:

$$v = \frac{\int v \cdot \mu_B(v) \cdot dv}{\int \mu_B(v) \cdot dv}$$

where μ is the output membership function.

We must emphasize the fact that:

- the P.I.D. parameters are easy to get as they are those found when tuning the machine; these parameters have been changed several times, but their value is always nearly the same;
- fuzzy membership function parameters are very easy to find, only one or two excavations - 3 hours - would be necessary; when there is a change of set-point, membership function

Comparison of Pressure Control with and without Composite Control

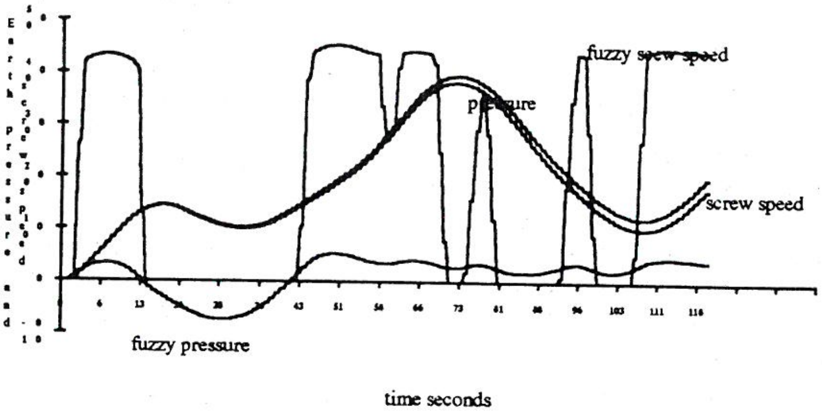

Figure 4. Comparison of Pressure Control with and without Composite Fuzzy Control

Comparison of Pressure Control with and without Composite Control with Gain of Oscillations Due To Disc Rotation Multiplied by 2

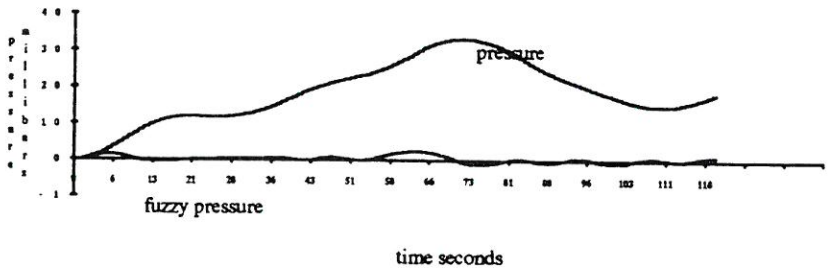

Figure 5. Comparison of Mismodelled Process with Traditional and CFCC Control

parameters should be translated around this new point.

Some problems are faced with, which cannot be neglected:

- determination of fuzzy control gain: this has been made by simulations evincing a good behaviour for a wide range of values;
- actuator saturation: in case of high saturation some rules have to be "frozen" to avoid undesired behaviour: in some cases, optimal control is higher than saturation value: a bad effect of our control would be diminishing, by a certain number of rules, this saturation;
- asymptotic zeroing of closed-loop error is achieved by introducing a fuzzy integral term when closed-loop error is medium.

In conclusion of this part, we can see that Composite Fuzzy- conventional control is an easy one to tune, as the number of parameters is reduced: closed-loop control is often already in place, and fuzzy rules do not need be accurate as the error is relatively small. Results prove that our control can do nothing but ameliorate traditional control, or fuzzy control without composition.

The remaining problems will be the same as in fuzzy control applied alone: it is difficult to ensure high performances.

4. Conclusion

Composite Fuzzy-Conventional control offers a good alternative to the complexity of fuzzy control parameters tuning. It is quite simple to tune in case of real processes where P.I.D. tuning is already known and where certain operator knowledge can be used.

It could also help experimented control engineers design their control methods by adding qualitative fuzzified remarks, that is to say, implement experimental knowledge by combining the algorithm with a fuzzy controller in order to improve performances.

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