Design of Industrial Multivariable Fuzzy Controllers

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Abstract: The control of large multivariable industrial processes whose dynamics is either unknown or vague-makes a very serious challenge in Process Control. The hitherto available conventional, classical techniques were very limited, complex and rarely satisfactory. Modern multivariable control theory, though powerful, has also met with limited application in the process industry. With the uncertainty and vagueness which are invariably present in the process dynamics, statistical techniques have not proved generally successful either.

Over the last fifteen years or so, the process industry has made serious progress in putting Fuzzy Logic into practice. Indeed numerous successful applications in a variety of process industries have been reported and more, no doubt, will be reported as the technique diffuses into the process industry with time. The design of Fuzzy Controllers today is very much an art and there are few effective design tools available now for their development. Regrettably, this fact has considerably limited their application .

To this end, this paper describes a PC-based, integrated development system which is flexible and let the controller designer test hypotheses, examine rule validity and rule conflict, examine the effect of changes in the controller parameters and perform a complete off-line simulation of a proposed Multivariable Fuzzy Controller.

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1. Introduction

The process industry has serious control problems which have hitherto defied solution using any of the conventional analytical techniques. Most recently, however, the application of Fuzzy Control, based on Zadeh's Fuzzy Logic theory [Zadeh 73], has proved very effective in offering solutions to many of these problems. Numerous industrial Fuzzy Controllers have been successfully commissioned in a variety of process environments [Holmblad & Ostergaard 81, King & Mamdani 74, King & Karonis 86,88, King 92, Mamdani 74] and there is a number of them presently commercially available.

Two serious problems encountered in practice in the process of developing a rule-based Fuzzy Controller, other than that of eliciting the rules whereby a process is manually controlled, are **rule validity** and **rule conflict.** Different human operators quite often specify *different* control actions for the *same* process conditions. This conflict, usually brought about by an incomplete knowledge of the process behaviour, very often has adverse effects on the operating conditions of the process and consequently determines a loss of production. It is a commonly observed phenomenon, in any case, that for any given process, productivity can dramatically vary from operator to operator during each shift,thus implying different degrees of understanding of the process dynamics and of the rules by which the process should be controlled by the operators. Other problems common to Fuzzy Controller design are:

- debugging,modification and testing of the control logic which can be extremely time consuming. From a purely pragmatic viewpoint,it makes sense to consider more efficient ways of implementing the heuristic part of the algorithm [Åström et al 86]. Making reasonable assumptions on the fuzzy sets (e.g. assuming a symmetric triangular form), often simplifies the control algorithm and speeds up computation significantly,
- necessity for implementing extensive error-handling and recovery code, making the software robust and commercially viable,
- enhancement of the re-usability of code for a new controller for a different process.

Although some of these design considerations can be met imperatively, others are amenable to trade-offs.It is generally impossible,or at least impractical, for the controller designer to exactly characterise what is meant by an optimal design at the outset. In this context,the term *optimal* can only be viewed in a heuristic sense. Except in the simplest cases, achieving anything close to optimal would be impossible without the repeated intervention of the controller designer because multiple performance trade-offs are bound to appear in practice. Accordingly,flexibility and a user-friendly man-machine interface are essential and central features of the proposed Development System.

Even if a Fuzzy Controller is found to perform on-line correctly and efficiently, a user may still have certain qualms for the following reasons [Boehm et al 78]:

- the controller may be difficult or impossible to modify,
- the controller may be difficult to use or easy to misuse by the plant operators,
- the controller software may be machine-dependent or difficult to integrate into the conventional production management and control system of the plant.

This is a problem of *evaluation* which is essential in determining whether the Fuzzy Controller meets the requirements and objectives specified at the outset or not. An evaluation identifies those costs and benefits [Davis 74] that deviate from their original estimate.

2. The Multivariable Fuzzy Controller Development System

When dealing with Fuzzy Controllers it cannot be hoped that the rules provided by the process operators or the production manager will lead to a feasible controller whose performance best matches that of a human operator. Indeed, to get to this end a fair amount of experimentation (or "trimming") is required, not unlike that necessary for commissioning a conventional controller. In doing so, the controller designer would usually like to interactively modify controller parameters or re-examine specifications with a view at finding a compromise solution. Such interaction is an integral part of any iterative design procedure and one which is effectively provided by the proposed development system.

A Fuzzy Controller typically involves a set of conditional **if- then** production rules whose antecedents and consequents completely specify the desired linguistic actions to be taken. The proposed Multivariable Fuzzy Controller permits a maximum of three antecedents (i.e. inputs) and up to five consequents (outputs). This number has been found to be sufficient for most industrial controllers. Consequents from different rules are numerically combined by means of the union operator. Both max product (due to Larsen) and min max (due to Mamdani) inference are provided and a comparison of the two methods can readily be made.

If more than one rule is fired simultaneously, a conflict resolution method (i.e. defuzzification) such as the centre of gravity (COG) or the mean of max. (MOM) method can be selected to infer the unique controller decision [Mamdani 74].

This paper describes an integrated PC-based Fuzzy Controller Development System for the design,testing and evaluation of industrial multivariable Fuzzy Controllers. The complete software package is written in C for fast execution and for ease of interfacing with other programs. In an attempt to simplify real-world controller design, a two-module structure is adopted, so that the controller designer must go through the process of designing a controller systematically and thereby avoid errors.The Development System comprises the following **two** modules:

- the **Definition Module (DM)** which allows for the definition of
  - the names of the control and process variables as well as their nominal values and permissible ranges,
  - the fuzzy sets for the various linguistic operators and
  - the conditional rules which constitute the knowledge base
- a **Test Module (TM)** which can perform both
  - static and
  - dynamic simulation

under various operating conditions, allowing the process engineer to examine the decision-making capabilities of any proposed fuzzy controller with a view at improving its performance.

The flexibility of the man-machine interface (MMI) of the Development System allows the user to easily modify the parameters of the Fuzzy Controller. Thus the fuzzy membership functions can readily be altered in order to observe the effect of changes of their shapes and their locations in the universe of discourse on the control decisions. Likewise,the conditional **if-then** rules, which establish the controller knowledge base, can be inserted,deleted and edited at discretion. An important feature of the Development System is the ability offered to process operators for visualising the rules by which they can control a process not as a series of linguistic **if-then** statements,very difficult to interpret globally, but **chromatically** as a multicoloured display of rule tiles, the colours of which are coded so as to give a visual indication of the consequents of the various rules. If confronted with a colour presentation of the rules, knowledge engineers and process operators can immediately examine the validity of the conditional rules and identify any possible conflict which can readily be edited. The ease with which rule validity and rule conflict can be resolved is a major feature of the Development System.

3. The Development System Functions

The opening screen of the Development System is shown in Figure 1.

The basic functions of the **Definition Module** of the Development System are shown in Figure 2 and are subsequently defined in more detail:

In the first option of the Definition Module, the controller and the process output variable names are specified so that all subsequent references to these variables be made in their engineering terms. The second option of the DM allows for specification of the permissible ranges of the controller and output variables since the Fuzzy Controller is incremental by nature. This is necessary because the linguistic terms "very high" (VH) and "very low"(VL) must be interpreted numerically from transducer measurements and ultimately be translated into numerical variables so that they may be transmitted to the appropriate controller actuators. The actual output of the controller $\mathbf{u}(k)$ is then

$$\mathbf{u(k+1) = u(k) + c(k)} \text{ for PI action or}$$

$$\mathbf{u(k+l) = u(0) + c(k)} \text{ for P action only}$$

$$\text{where } \mathbf{c(k)} = \Re\,(\mathbf{y(k)-y(0)})$$

is the Fuzzy Controller incremental output, $\mathbf{u}(0)$ and $\mathbf{y}(0)$ are the nominal control input and nominal process output and are normally specified by the operator whilst $\mathbf{u}(k)$ and $\mathbf{y}(k)$ are controller output and process output variables at any time instant k. In either case,whenever the operator makes any change in the nominal process output,then $\mathbf{u}(k)$ is set equal to this new nominal value. The operator $\Re$ specifies the functional mapping between the inputs and the outputs of the Fuzzy Controller and is defined by the rule base.

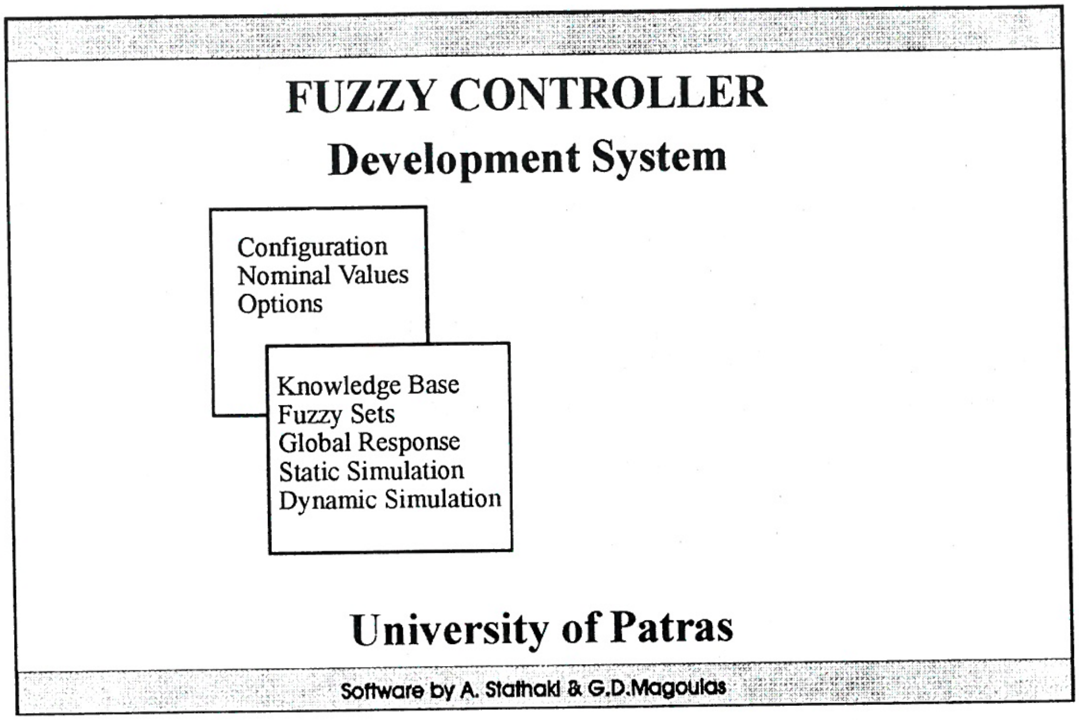
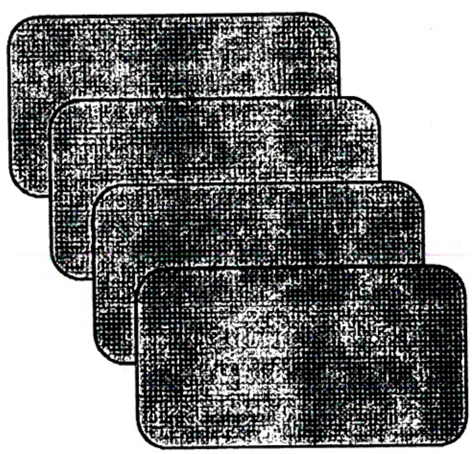


Figure 1. The opening screen of the Development System



1. Input-Output Variable Names
2. Permissible Ranges of Variables
3. Fuzzy Set Distribution Functions
4. Rule Base

Figure 2. The Definition Module

Five distinct **fuzzy sets**, one for each linguistic level (VL for very low, LO for low, OK for acceptable, HI for high and VH for very high respectively) must be specified in the third option of the DM. The **knowledge (or rule) base** by which the Fuzzy Controller infers its decisions is specified in the fourth and final option of the DM. The number of inputs to the controller has been limited to three,

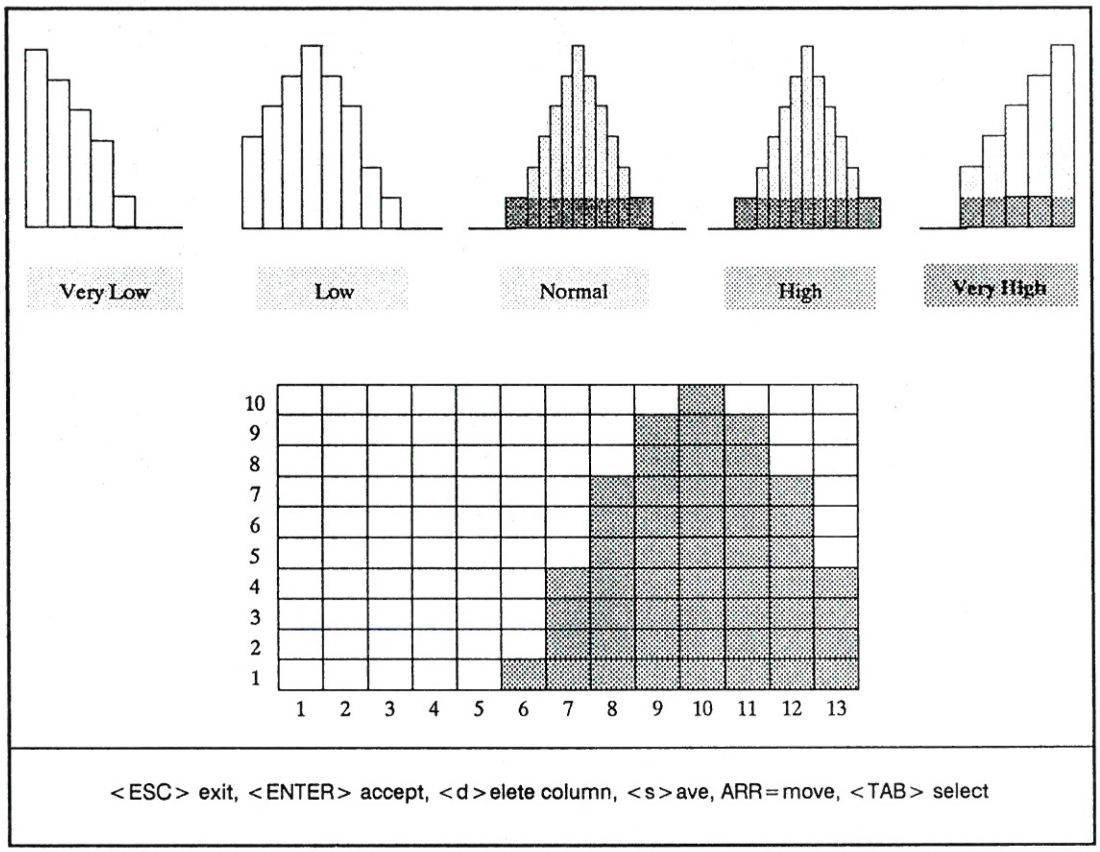


Figure 3. The Fuzzy Sets Option

Experience has shown that in an industrial environment this number of linguistic levels usually suffices to describe the necessary production rules by which the Fuzzy Controller infers its control action. Rarely, in any case, do human operators describe their control actions in more linguistic terms. These fuzzy sets are discretized into 13 *singletons* over the universe of discourse and are presented in bar-graph form as in Figure 3. Each fuzzy set can be specified independently. For convenience the height of each singleton is quantized into 10 distinct levels as finer quantization has not been found as necessary. Indeed recent research has shown that the controller decision is insensitive to small changes in the height of each singleton [Boverie et al 91].

a number that has been found sufficient for most industrial processes. If more than three controller input variables are necessary then a hierarchical structure can be adopted [Saridis 79] wherein a multi-level architecture is formulated. At the lower level of the hierarchy a series of parallel three-input multi-output Fuzzy Controllers are established, and are co- ordinated by a higher level supervisory Fuzzy Controller [King & Karonis 88]. The knowledge base of each Fuzzy Controller is presented as an exploded 5x5x5 three-dimensional (Rubik) cube i.e. as a sequence of 5x5 *tile squares* (not every one of which need be specified) as shown in Figure 4.

For lack of colour the tiles are shown here as a series of grey shades instead of *chromatically*

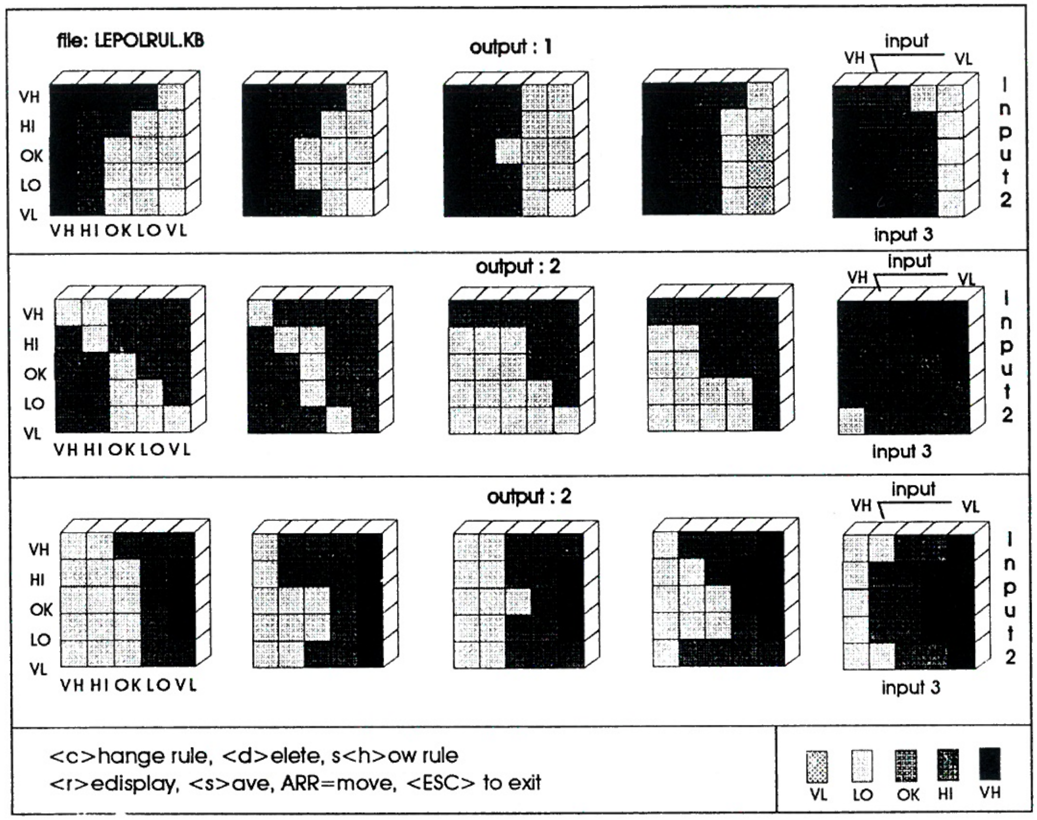


Figure 4.Knowledge (or Rule) Base Tile Squares

as on the computer screen. Each *tile* represents an element of the control space the size of which is defined by the permissible range of each variable divided by the number of elements used to quantize the control space.It is evident from a cursory glance at this rule-pattern that any rule inconsistency can be detected immediately.

The very first matter which the fuzzy controller designer must contend with, after he/she has elicited, coded and stored the rules in the knowledge base,is **rule-consistency.** It is unlikely,for instance, that adjacent rule tiles can indicate a rule transition from,say, VL to VH as this would imply a radical control profile which is most unlikely to exist in practice.Likewise there cannot be more than one linguistic level change from tile to tile. With experience a number of pattern rules can be developed to help the designer in examining and often questioning the **validity** of the rules elicited from the plant operators. Very often, in fact, plant operators must be questioned again on their decisions in the light of rule inconsistencies. Indeed when faced with the obvious inconsistencies which the colour-coded rule-tiles offer, operators immediately appreciate their errors, retracting,modifying and learning the corrected rules and become better operators as a result of this experience.

The **Test Module** has two functions:

1.Static Simulation and

2.Dynamic Simulation

In the first function of the TM, that of **static simulation**, the numerical values of the input

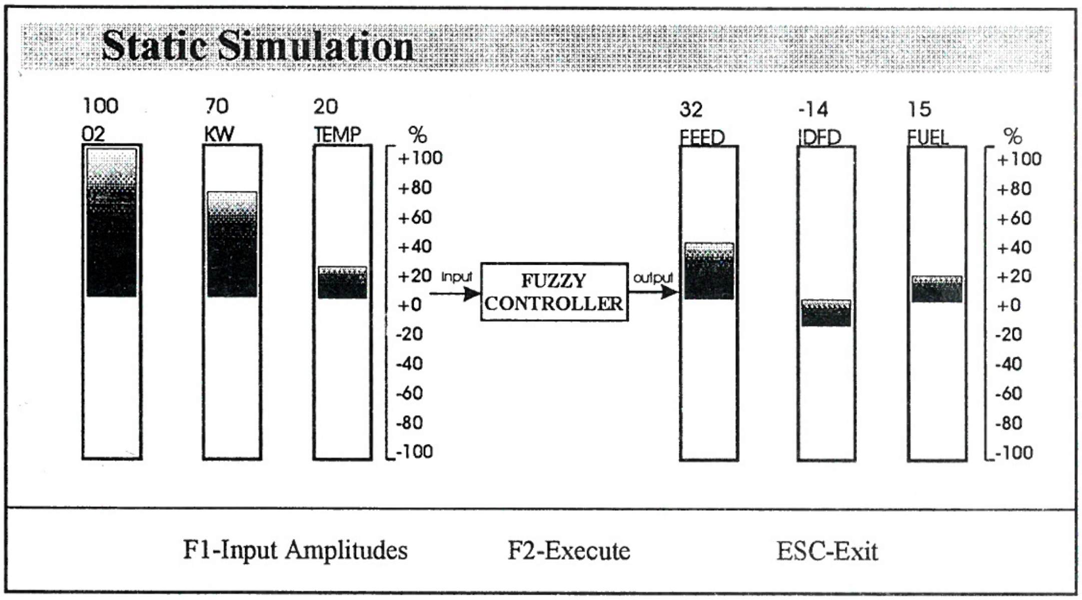


Figure 5. Static Simulation Option

variables must be specified as a percentage of the permissible deviation of each variable and the Fuzzy Controller is then instructed to execute and display its decision, yielding the controller inputs and outputs as bar- graphs as shown in Figure 5. The Development System being integrated,it is a simple matter to return to the knowledge base or fuzzy sets options, make changes and re-execute the controller to observe the changes in controller performance as a result.

The second option of the TM, that of **dynamic simulation**, is similar to the first with the difference that now each time the controller executes a random number, generator produces a sequence of uniformly distributed random values for the input variables.Two display forms are possible:the first is identical to the static simulation option except that the bars change continuously in response to each execution of the control algorithm, and the second shows a time response which is a moving plotter-like display as shown in Figure 6.

4. Application Example

By way of example, the design of a multivariable Fuzzy Controller for a large-scale industrial process (a cement mill) was studied exhaustively. Following the discussions with the process manager,the process output and control variables were first specified as were their permissible deviations from their nominal values. The next and most crucial stage was knowledge elicitation, a task that often proves to be difficult and frustrating. Eight experienced operators were supplied questionnaires requesting their decisions on all possible combinations of the process output variables. The process having three variables each of which was described at five linguistic levels,

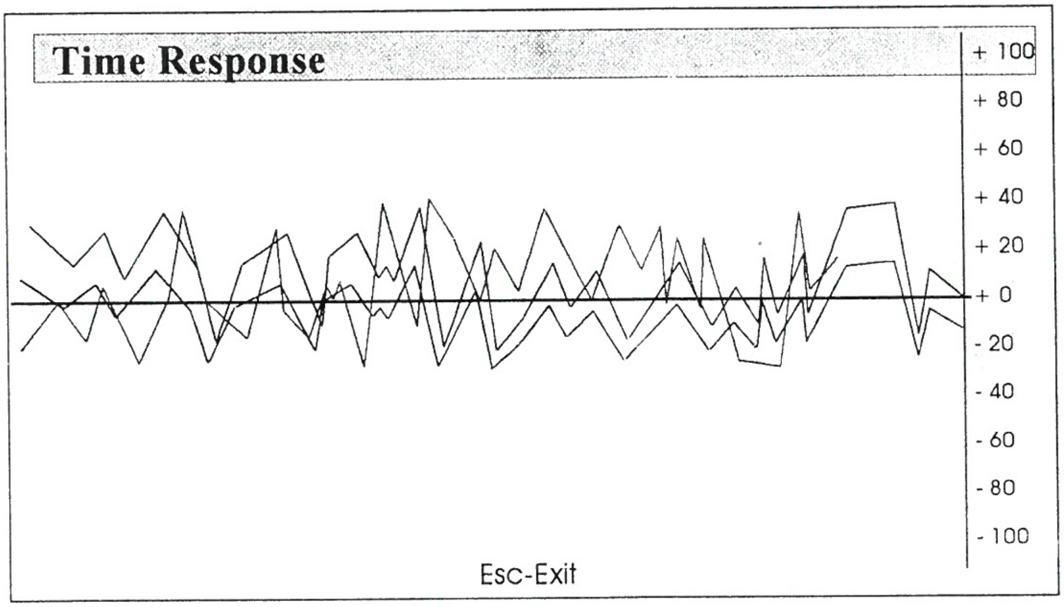


Figure 6. Dynamic Simulation Option

responses to a maximum of 5x5x5 = 125 rules were required in linguistic terms (i.e. VL,LO,OK,HI or VH). There being three control outputs it is obvious that three responses to each input state were solicited.

Perhaps not unremarkably the responses so elicited showed a wide discrepancy of control actions, at times widely different,even opposing, for the same plant conditions. The results for any given operator were fraught with conflict and at times it was difficult to believe that they were cognisant of their actions. Erratic actions showed up immediately in the colour-coded rule-tile displays. If the control actions of different operators were placed side by side and compared it would prove generally impossible to find common actions. Taking the average of all the plant operator control actions for each plant state proved futile due to the widely differing and often opposing operator decisions. The overall results in this case simply averaged out mainly to an unacceptable "do nothing" response! Taking the majority action as the basis of the rule base, on the other hand,yielded somewhat more acceptable results but here again rule conflict was still very much in evidence.

Faced with these conflicting decisions, a process of rule editing in which a logical step-by-step procedure was followed led to the finai "logical" rule-base where all conflicts were resolved.The following axiom has been formulated and consistently applied to reach at a "logical" rule-base:

There cannot be more than one linguistic level increment or decrement in deviating from any given rule-tile in any direction.

Following a small number of visual passes for each tile-floor,it rapidly becomes evident which rules must be edited in order to resolve rule-conflict and reach a "logical" rule-base. In fact, following this procedure for a large number of cases and processes which Fuzzy Controllers were being designed for, it became evident that knowledge elicitation would have been infinitely easier,faster and more precise if the human operators had stated their decisions directly in colour-tile form on the Development System and this procedure had been recommended.

5.Conclusions

The PC-based Fuzzy Controller Development System provides an integrated environment in which the controller designer can develop and experiment industrial Multivariable Fuzzy Controllers. The Development System has been used with success for the design of a number of industrial multivariable Fuzzy Controllers for the cement industry which have subsequently been commissioned. The Development System has proved particularly effective in establishing and clarifying rules by which human operators control a process as well as very powerful as a test bench for comparing the decision-making process of a Fuzzy Controller with that of a human operator. Yet another feature of the Development System is its ability to train new process operators off-line without any fear to the process itself.

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