FUZZY SETS THEORY AND PROCESS CONTROL

PAST, PRESENT AND FUTURE

by

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ABSTRACT

It is now some 15 years since the first "fuzzy controller" was implemented as an experimental system by one of the the authors and his associates. Today this work occupies a prominent place within the larger areas of both control systems and fuzzy sets theory and there is an extensive and growing literature on the subject. In this paper we take a retrospective look at that original study and describe how and why it came about. It is not the intention here to present a survey of current blossoming work on fuzzy control. However, we present some reflections on the importance and the nature of this work. Finally, the paper indulges in some projections concerning fruitful avenues of future research. One key point put forward in this paper is that the original study was aimed more at control engineering than at fuzzy sets research, and so the projections in this paper also address the same control engineering community.

1. INTRODUCTION

It is now some 15 years since the first "fuzzy controller"was implemented as an experimental system by the author and his associates [Mamdani & Assilian (1975)]. Today this work occupies a prominent place within the larger areas of both control systems and fuzzy sets theory and there is an extensive and growing literature on the subject. In this paper we take a retrospective look at that original study and describe how and why it came about. It is not the intention here to present a survey of current blossoming work on fuzzy control. However, we present some reflections on the importance and the nature of this work from both the fuzzy sets theory and the control theory point of view. Finally, the paper indulges in some projections concerning fruitful avenues of future research. One key point put forward in this paper is that the original study was aimed more at control engineering than at fuzzy sets research, and so the projections in this paper also address the same control engineering community.

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2. RETROSPECTION

It should be remembered that at the time of the original study, terms such as "expert systems" or "rule-based systems" had not been coined. The question that was posed for that study was that if a control engineer was faced with a process that was so complex that it was not easy to derive its mathematical model accurately, then how could AI ideas be applied profitably to design a controller for that process? It was never the intention to apply fuzzy sets theory to the problem; indeed that theory itself was new then and very few research workers had any familiarity with it. The original study was at first viewed mainly as an application of machine learning in some form.

2.1. Machine learning applied to control

Machine learning covers a wide spectrum of possible mechanisms from parameter tuning to adaptation, supervised learning and completely un-aided self-learning. Adaptive control was already a popular research activity. Unfortunately, in its many forms, even this required some understanding of the process model expressed in a numerically mathematical form. The intention was always to see if one could get away from a numerical representation of the process because surely the human operator who coped with the process adequately only had a qualitative understanding of it. Initially, therefore the work was seen mainly as some form of supervised machine learning system. In such a system the human operator would control a complex process via a machine on which the learning algorithm was also implemented. The machine could therefore, observe both the state of the process and the action taken by the operator. The learning algorithm would use this information to discover the policy of applying the appropriate action in each state.

One reason the supervised learning approach did not work satisfactorily was that a crucial piece of information waslacking to aid the learning algorithm. The human operator was prone to an occasional error (a) of which he was often unaware,and (b) from which he could usually recover (mainly because human designed systems are usually quite robust). Such an occasional erroneous data would nevertheless play havoc with most learning algorithms. The result was that the overall performance of the learning algorithm was inferior to that of the human operator.

2.2. Fuzzy sets applied to control

The alternative to supervised learning appeared to be a system in which the operator would "tell" the machine what rules he was using in controlling the process. In a sense this could also be viewed as a form of learning - learning by being told.The motivation was the work of Feigenbaum et.al. (1971) on DENDRAL. At first a DENDRAL like system was being constructed but this was soon overtaken by the appearance of a seminal paper by Zadeh (1973). It is a tribute to Zadeh, that the style of that paper brought fuzzy sets theory within easy reach of newcomers to the field. Furthermore, it described exactly how one could go about constructing a rule based system. So that in a sense, the fuzzy control work was not a novel application of fuzzy sets theory. The novelty lay in the way control could be carried out using rules.

Fuzzy sets ideas were amazingly easy to apply and the control algorithm was constructed and tested within a week of reading the paper by Zadeh. There were three key aspects to that original work. These were:

- A novel way of designing controllers of certain types of control systems.

- An application of rule-based systems in control of industrial processes.

- An interesting industrial application of fuzzy sets theory.

We will consider these three aspects in some more detail in the next section. Here it may be useful to remark that the above list also represents the order of importance of the three aspects. The reason "fuzzy control" looms large within the fuzzy community is firstly, that it was the first real application that the community could point to; and secondly, that the control engineers who wanted to pursue this work further could only do so as members of the fuzzy community because the control community largely ignored the work until recently. It should be noted that Zadeh put forward the concepts of fuzzy sets largely because of his dissatisfaction with the increasing and unnecessary mathematical rigour in control theory and so it was fitting that the first application of his theory was in the area of control engineering.

3. REFLECTION

What has been discussed above suggests that "fuzzy control" is perhaps an unfortunate term to have gained currency. The main point was that the system represented a rule-based control implemented using fuzzy sets theory. Let us now analyse in some more detail the three features of the initial "fuzzy control" work.

3.1. Rule-base control using fuzzy sets

The emphasis here is that control of complex processes can be carried out in novel ways without recourse to traditional methods using numerical mathematics. Since the last war the emergence of control theory has done a great deal to increase automation in process industry. This advance has resulted not only in much increased productivity, but also in more reliable plants and more consistent products. However, the very success of this essentially analogue approach has meant that many academic control engineers have felt that it can be applied to any situation. The true future impact the digital computer revolution has remained unrecognized by these engineers. They have so far seen the digital computer merely as another way of implementing numerical computation.

Artificial Intelligence emphasizes symbolic, non-numerical computation, but control engineers have, for a long time, remained oblivious of AI's potential impact on process control. Rule based control using fuzzy logic is merely the first beginning of AI, particularly knowledge-based systems, in lower level-control; that is, control applied to situations with process complexity. We explain later in this paper that process complexity refers to involved, ill-understood and many variable interactions within a process itself and it differs from organisational complexity. This kind of situation is normally manifested in chemical processes. The "fuzzy control" system was really only targeted towards these type of processes. It is not surprising, therefore, that one of the first applications of the approach appeared in the cement industry because the chemical reactions that take place inside a cement kiln are almost impossible to comprehend and represent precisely. The cement industry was one of the last basic process industries to address the question of automation. This question came up mainly because energy costs started increasing in the early '70s. Thus the main requirement was to reduce fuel costs. By all accounts, fuzzy control approach has succeeded in doing that [see Haspel (1986)].

Fuzzy control had another property as well which increased its appeal beyond that of controlling systems with process complexity. Some research workers at Delft University [Kickert & Van Nauta Lemke, (1976)], in the early days of the "fuzzy control" research, were able to show that the approach appeared to be robust when the control system was subjected to noise. Unfortunately this was only possible to show experimentally, because the method was not amenable to a mathematical analysis.

3.2. The application of a rule-based approach to control

It seems intuitively obvious that what makes the so-called fuzzy control approach successful is its rule-based nature rather than its use of fuzzy sets. This may come as disappointment to the fuzzy community but nonetheless has to be acknowledged. "Fuzzy controller" has many of the characteristics of expert systems. However, as expert systems go, the rule-based fuzzy controller is remarkably simple in its structure. Control is normally achieved by means of only a few rules which can be grouped together into well defined structures.

In a rule-based controller like with any rule-based system, the main effort has to be expended in acquiring the control rules. The first cement kiln controller was largely derived from rules that were already available in a kiln controller'straining manual (Peray & Wadell 1972), but even these had to be carefully tuned.

Researchers working with expert systems have quite rightly identified knowledge acquisition as the one area that can demand a great deal of effort when building a rule-based system. Psychologists have moved into this area with an armory of interview techniques and so on. One cannot help but feel that the approach adopted by these psychologists can often make the problem appear more difficult than it really is. In the early days of fuzzy control a study of process control task by Bainbridge (1974) arrived at largely negative conclusions concerning any hope of finding good control rules. It should be borne in mind that engineers and designers do possess a large amount of knowledge and that AI is not entirely or even predominantly about knowledge acquisition.

A set of control rules is made up of individual rules that, in some applications, interact. Therefore, it is not simply a question of acquiring each rule at a time, but the whole set must be finely tuned to produce the desired results. More recent work of self-learning fuzzy controllers [Sugiyama, (1986)] appears to be better at acquiring the rules by an iterative learning process. However, so far as is known, such self-organizing techniques have not yet been tested rigourously in real industrial situations.

3.3. Fuzzy sets and control

It has been mentioned earlier that the fuzzy sets theory itself plays less of a role in the success of a "fuzzy controller" than has been supposed. This is not to say that its role is merely accidental and of no material value. It makes the implementation of a rule based system far easier than by any other means. In this respect, fuzzy sets theory has filled the gap between numerical computations and symbolic manipulations with sets. The theory takes care of a remarkable amount of detail while the designer can focus on the key issues concerning the knowledge being encoded. Even if the state space itself is not discretized explicitly (in fact one gets a smoother control if this is not done), the definition of the fuzzy variables acts as a conceptual form of discretization. The state space can then be covered by a few well chosen rules, leaving the action for the rest of the space to be derived through interpolation by the application of the mathematics of the fuzzy sets theory. It is doubtful if any other method of implementing the control rules can provide this smoothing mechanism in as parsimonious a fashion.

4. CURRENT WORK

It is not the intention of this paper to give a review (exhaustive or otherwise) of current on-going research in "fuzzy control" or even to survey how this method is being applied to-day. A good survey of work being done until about 1985 can be found in Mayers & Sherif (1985). In the last three years alone there has been a great proliferation of "fuzzy control" *applications* [see, for example, the proceedings of IIZUK-88, (1988)]. This flowering of applications has brought with it new changes to the state of the art itself, which hopefully, someone soon will undertake to review. Our intention here is to comment on the impact of this, and more generally the KBS applications, to control engineering.

4.1 Current responses of control engineers to AI applications

Although the researchers working on "fuzzy control" are still mainly able to present their findings within the fuzzy sets oriented journals and conferences, there are signs that the control engineering community is beginning to pay attention to not just the subject of fuzzy control but also to symbolic computation and AI applications in general. However, the predominant view of the control community to expert systems is that these can play a useful role in control system design, but at the periphery of the mainline control area only. This view is expressed by Clarke (1986) and Atherton (1986) who say effectively that expert systems can be used for say tuning the parameters of an adaptive controller. However, in their view the core of any control system will continue to be based on numerical techniques. There may be a few systems with process complexity in which rule based systems like fuzzy controllers maybe the proper way to go but that such systems will be few and far between. In short, the control community's view of AI, expert systems and fuzzy control is still conservative - in our opinion, more than it needs to be.

4.2 Fuzzy hardware system development

A important recent trend arising from the fuzzy control workers is the special purpose fuzzy control computers. Starting from 1986 several hardware systems have been produced (e.g. [Togai & Watanabe (1986); Takeshi (1986) and many more]. Their application to robust control of processes have been demonstrated on experimental systems and are at present being produced in larger numbers for commercial exploitation in industry.

The work on such hardware has shown that even many of the control rules are not dependent on the application domain but are in fact general purpose control rules. In its simplest form, the "fuzzy computer" is little more that a form of PID controller. But because, not only the gains but also the underlying rules can be changed easily, it has a wider application. In particular a fuzzy controller is undoubtedly more robust to noise and parameter changes within the system being controlled than the conventional controller.

5. PROJECTION

So, not only "fuzzy control", but also fuzzy sets theory itself presents an alternative approach to what is perceived as a narrow mathematical approach to control system design. Both point to the usefulness of a symbolic approach to dealing with complexity. In talking about complexity, it should be pointed out that two types of complexity can be distinguished. The first is the process complexity already mentioned earlier. The other refers to the plant complexity which we refer to as organizational complexity. Potential applications of AI to requirements arising out of plant complexity are shown in Table 1 reproduced from Efstathiou (1986). "Fuzzy controller" is aimed at process complexity but AI in general can help with systems that exhibit organizational complexity. The main emphasis in the future work is thus towards tackling ever more complexity in process control rather than encouraging the use of more sophisticated fuzzy sets mathematics in implementing fuzzy controllers. Before discussing the possible future work it may be useful to state what coping with complexity means.

5.1. Coping with complexity

Coping with complexity is the predominant characteristic of AI systems. However, the difficulty with an intuitive feel for this concept is that it may simply reflect the designer's or the proposer's subjective feeling based upon his lack of proper understanding of the problems. It is necessary, therefore, to ensure that objective notions are established for a proper discussion of complexity. It is too ambitious to expect that these notions can be translated into criteria and metrics for the assessment of complexity. One such notion is "coping", and that is discussed next.

We use the term "coping" where the handling of complexity is concerned to emphasize the fact that coping is the best one can do under complexity (whatever complexity may mean - indeed there may be many types of complexities). Coping means that with complexity, one is not necessarily after complete or optimal solutions to problems. Any solution that does not lead to disasters will do. Indeed if an AI solution can guarantee that disasters will be avoided always, then such an approach can be deemed to have succeeded remarkably. However, "coping" is even a weaker notion than that because a technique may only be able to demonstrate it has avoided disasters in all situations so far encountered without it being possible to analyse the technique to see this will always continue to be so. The reason is that AI techniques are never meant to be a complete expression of the solution method. A prudent AI design does not insist on finding a complete representation, rather a good design should admit failure to find a solution instead of proposing wrong solutions.

5.2. Naive physics, deep knowledge and qualitative reasoning

These are areas of AI research that have the potential for application to systems that are organizationally complex. Of these, Naive physics is essentially a philosophical and a theoretical programme which underpins the more application oriented work of deep knowledge and qualitative reasoning.

There is now a growing literature on the representation of deeper knowledge than is exploited in rule based systems (which normally encode knowledge at a shallower level). In industrial processes there is extensive knowledge available concerning the structure and the function of the plant. Deep knowledge does not imply that encoding of knowledge extends to the most basic elements of the system. The depth of knowledge is relative and merely deeper than in the usual shallow systems.

From the point of view of process control, it is the work on qualitative reasoning [see for example, the book edited by Bobrow (1984) for a good resume of key work on qualitative reasoning], that has the best potential for application to organizationally complex systems. Simply stated, this research aims to represent the system variables qualitatively rather than numerically.

Comparing the qualitative reasoning approach and the fuzzy control approach, it is easy to find many similarities between them. The essential element in both approaches is that qualitative values are used to represent reality. For example, the simple quantity space in qualitative reasoning is reduced to three elements: Positive, Negative and Zero which are used to signify that the variable value in question is increasing, decreasing or is unchanged. In "fuzzy control", on the other hand, variables are often encoded as Positive Big, Positive Medium etc. The difference is not just the way the variables are encoded but also in how they are treated. Qualitative reasoning approach is algebra oriented - an algebra for manipulating the combination of signs is created: (see [Struss, (1988)] and [Stipanicev, (1989)]) while Fuzzy control is fuzzy sets oriented. Qualitative reasoning has its weak points, namely that the simplicity of representation is obtained at the price of often not being able to generate unique solutions. On the other hand, Qualitative reasoning has shown many novel ways of modelling the process and despite possible ambiguities, give rise to ways of efficient computer prediction of plant behaviour under complex situations.

As has been mentioned, "fuzzy control" is primarily aimed at process complexity. In dealing with plant complexity, it is necessary to have a computer model of the plant from which predictions can be made. In effect it is the form of complexity that requires the effect of possible actions now to be evaluated with respect to possible future behaviour. "Fuzzy control" in its elementary form is based on heuristic rules about direct control procedures, and not on system model. A qualitative model, as opposed to a numerical model, is able to incorporate a great deal of common sense information about a plant. At present most work on qualitative reasoning has only tackled toy problems. There is a need to evaluate how these techniques may scale up.

6. CONCLUSIONS

The "fuzzy controller" was introduced as the first rule-based controller to control processes with a complexity such that it was not possible to derive a mathematical model. It was successful because of its rule-based nature rather that its use of fuzzy sets. This is not to say that the role of fuzzy sets theory was unimportant. It made the implementation of a rule-based system far easier than by any other method.

Today the "fuzzy controller" is in its mature phase as pointed to by the proliferation of industrial applications and the creation of "fuzzy computers". The future work must be towards tackling more variety of complexity of the industrial plant rather than delving into the fuzzy mathematics of the "fuzzy controller". A most promising area is dealing with plant complexity, where a combination of concepts arising from "fuzzy control" and qualitative reasoning could form a good line of attack.

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TABLE 1 ***The Range of Activities covered by Industrial Process Control***

Activity	Time-scale	Kind of knowledge	Kinds of inference	Linked on
Low-level Control	Hours to Years	Process & Plant	Forward chaining. Backward chaining. Qualitative simulation. Hypothesis list management. Test generation.	Plant re-configuration
Scheduling	Weekly	Plant	Constraint Matching. Constraint specification Schedule generation. Schedule critiquing. Justification.	Refinement of Plant
Planning Design	Years	Process & Plant	Simulation. Critiquing Parts list generation. Risk assessment.	
economic	Years	Process (external world)	Simulation What-if scenarios. Plant refinement.	
Training		Process & Plant	Critiquer. Explainer.	