Model-Based Methods in Fuzzy Systems

Tapio Rauma & Kari Haataja
Intelligent Systems
VTT (Technical Research Centre of Finland) Electronics,
P.O. Box 1100, FIN-90571 Oulu, Finland
Phone: +358-8-551 2111, Fax: +358-8-551 2320
email: Tapio.Rauma@vtt.fi

ABSTRACT: In this study, different model-based methods and structures are studied in the light of their usefulness mainly in control systems. The methods are divided into three groups: using a model in testing possible control actions, forming a controller from the model, and using a model in a supervised learning system.

Fuzzy logic has been used in normal (rule-based) systems and in model-based systems. Reasons to use fuzzy modeling differ case to case. The reasons are analyzed based on writers' experiences in research and development projects during several years.

KEYWORDS: Model-based systems, fuzzy systems, decision making.

1. INTRODUCTION

Model-based systems are commonly used in the fields of expert, artificial intelligence, and control systems. In the field of expert systems in general, the model-based approach is seen as an alternative to rule-based systems.

The basic principles of fuzzy modeling were presented in 1973 by Dr. Lotfi A. Zadeh (1973). Since then, methods of constructing and using fuzzy logic based models (fuzzy models) have been developed and used in different kinds of environments. The main interests seems to have been modeling techniques and not on methods for using models in different reasoning systems.

In general, the model-based approach is used when some concrete advantages are attained with it. The advantage could be, for example, rapid development of a system, a more accurate and robust control system, or easier maintenance in future. In this paper, we concentrate on studying what is behind the scenes, in other words we aim at listing the pros and cons of the systems and structures that are used especially in the field of fuzzy logic. The methods presented seem to have their origin in research carried out in the fields of model-based controlling and, to some extent, in AI.

We present different types of model-based methods and discuss the possible advantages of them when fuzzy modeling is used. The background of this study is VTT Electronic's ongoing long term research in which the general model-based approach is studied, developed, and analyzed. The main goal of this research is to form methods for combining different model-based systems: for example combining fault diagnosis and control systems could provide great benefits. This sets special demands to the approach used: the modeling and control methods used should not restrict co-operation between the fault diagnosis and control systems. More information on the ongoing research can be found in Rauma (1996), Rauma *et al.* (1996) and Rauma *et al.* (1997).

2. WHY FUZZY MODEL-BASED SYSTEMS?

In general, the advantages of fuzzy systems can be classified into several groups [Pedrycz *et al.* 1993; Lee 1990; Takagi *et al.* 1983]:

- Development can be made rapidly (especially in prototyping)
- Multiple knowledge sources can be used (expert knowledge, different kinds of models, etc.)
- Uncertain and incomplete information can be used in developing the systems
- Reasoning of the system is human-like (therefore it is easy to understand)

From the viewpoint of model-based systems it is not always obvious why fuzzy system models, or fuzzy model-based systems, would be worth considering at all. In model-based systems, fuzzy modeling can be seen as an alternative to other modeling techniques. In such cases the problem can often be reduced to the eternal question about the accuracy of the constructed model, or then some other reasons for using fuzzy systems models instead of other techniques must be found. The reasons can thus be grouped:

1. Fuzzy system models are more accurate than models based on other techniques
2. Fuzzy system models appear to be more tempting than other models due to other reasons, for example maintainability or cost effective development

We can conclude from the lists above that fuzzy system models are worth of using when

- Plenty of knowledge is available, but traditional models are difficult to construct because of the konwledge being incomplete or having uncertain features
- The behavior of a system is difficult to represent mathematically (the process and its mathematical model differ considerably)
- The model is needed quickly

The first two points are supported by the general difficulty in representing uncertain information mathematically. In such cases a more qualitative approach is widely approved and used. The third point is based on the writers' experiences of several years: if there are many knowledge sources available, fuzzy systems can be built very rapidly (the usual case: data supported by expert knowledge).

Characteristics to rule-based and model-based methods are:

- Rule-based systems
  - ◊ knowledge is embedded into a knowledge base
  - ◊ difficulties in verification and validation (knowledge engineering)
  - ◊ one huge system that is difficult to divide into functional modules
  - ◊ precondition of maintenance is the total understanding of the system
- Model-based systems
  - ◊ all necessary information is in the model
  - ◊ the model can often be verified and validated, at least to some level of exactitude
  - ◊ the model and the decision-making can be divided into functionally independent parts
  - ◊ maintenance is carried out by updating the model (enhancing the existing model or installing a model based on some other method)

Most of the existing techniques and methods in the field of expert systems are based on rule-based methods, which can be seen from for example in Kandel (1991). Model-based systems are more common in control systems. If we analyze the recent trends in the field of fuzzy control systems, we also notice an increasing use of model-based approach in expert and decision systems. Therefore it is necessary to study the possibilities of using fuzzy model-based systems instead of normal fuzzy (rule-based) systems.

Combining the control and diagnosis procedures has been brought out as one prospective way in developing more intelligent control systems [Rauma *et al.* 1997]. This, and other possible combinations, will in all probability set new demands for the development methods and practices of model-based systems.

3. FUZZY MODELS IN CONTROL SYSTEMS

When model-based control systems are studied, three main structures emerge as the most used. Figure 1 presents simplified structures of a direct model-based system (a), and a system, where the model is utilized in constructing the control system (b). The third main class is performance adaptive model-based systems, where a model is used in evaluating the performance of a control system. This third approach, presented in Figure 2, is based on utilizing a model in performance evaluation and controller adaptation. Based on the evaluation, the parameters of the controller are changed.

All these three structures have some similar functional operations, but the division into these three groups makes it fairly easy to express the different aspects of model-based systems. Most model-based control systems can be defined as clearly belonging to one of these groups. However, we acknowledge that there are a lot of more or less tailored model-based systems that are difficult to put into any of these subgroups.

In the next chapters we will give more precise information on how these methods can be used. We also try to find out special advantages and disadvantages related to these methods, as well as suitable fields of application.

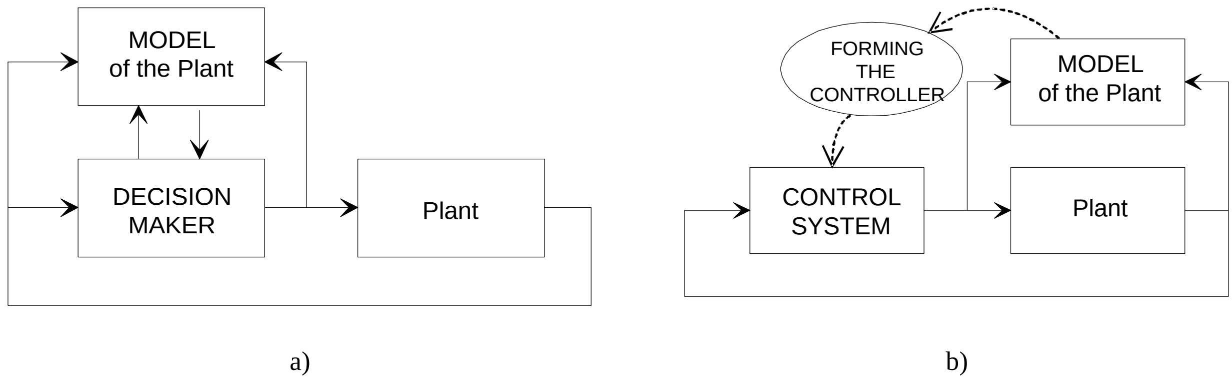

Figure 1. Two main approaches used in model-based control. The model is directly used in the control system in (a), and the model is used in constructing a controller in system (b).

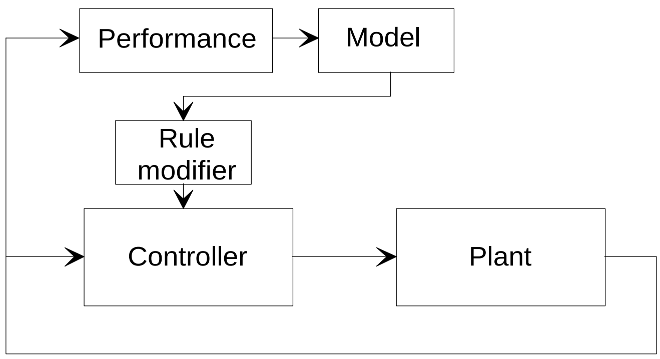

Figure 2. A model-based control system based on performance analysis.

3.1 THE BASIC MODEL-BASED CONTROLLER

The first type (Figure 1(a)) of model-based control systems is maybe the most used, because the model and the control system (decision maker) can be clearly separated. This makes the maintenance of the system easy, as, for example, changing the modeling technique will not affect the decision making at all. A simple way of installing this kind of system is described in Driankov *et al.* (1993), where a fuzzy system model is used. The basic principle is that the model is used as a test environment to find out the best control action to use in controlling the real process (Figure 3). Possible control actions are tested with the model, and the one that produces the best results is then chosen.

The essential parameter in decision making is the performance measure. The task fo the performance measuring is to provide the results of proposed control actions in order to find out the best available choice of action. Parameters such as overshoot, settling time, rise time, and frequency of oscillations (controller) are commonly used. The form of performance measuring changes from case to case. Especially in complex cases where analyzing the performance is not a simple task, the optimal solution is usually a compromise of several pros and cons. One way to carry out the measuring is to use fuzzy logic [Driankov *et al.* 1993].

A general weakness of the proposed method is that possible control actions should be defined before the method can be applied. Especially in complex MIMO systems, where the amount of possible control actions can be very large due to different combinations, it may be impossible to test all the possible combinations to find out the best one. This problem can be solved with a special optimization algorithm. Choosing an appropriate search algorithm can be a very difficult task, but the plain truth is that complex algorithms produce better results than simple ones. Unfortunately they usually take more time, are more complex to maintain, and are not as useful for general purposes than simple ones.

An advantage of this kind of system is that the type of the model can be chosen without restriction. This is beneficial if it seems that more accurate models can be produced later with other modeling techniques.

3.2 USING THE MODEL IN DEVELOPING A CONTROLLER

As in traditional control theory, a model of a system has been used in constructing a controller in the field of fuzzy systems (Figure 1(b)). As a matter of fact, already before the exact solution was found, a conventional process model and a fuzzy process model had been seen as possible knowledge sources in developing fuzzy logic controllers [Lee 1990]. Brown and Harris call this approach 'indirect learned fuzzy control systems' because the controller is formed from a learned model [Brown *et al.* 1994]. In direct learning, the learning procedure is directed towards parameters of a controller based on performance measurements (Figure 2).

A fuzzy system model can be utilized in several ways when developing a control system. In the simplest case the control or knowledge engineer can use the model to understand the behavior of the system to be controlled and possibly use the information (knowledge) in designing a control system. On the other hand, a control system can be developed directly by inverting the model. Fuzzy model inversion has been studied by several authors in the field of control and diagnosis. For example, in Babuška *et al.* (1995) an inversion of a fuzzy system model is used as a controller and in Rauma *et al.* (1997) the inversion is utilized in fault localization system.

3.3 USING THE MODEL IN ADAPTING A CONTROLLER

The system described in Figure 2 differs greatly from the ones described in Figure 1, but is presented because it is commonly used especially in fuzzy systems. The basic function of performance adaptive/learning is based on measuring the performance of the controller and changing the parameters of the controller, if needed. In Brown *et al.* (1994) the learning mechanism is composed of a performance index and a model. This structure is commonly used when self-organizing controllers (SOC) are developed. Perhaps the most famous methods of developing SOCs are presented by Procyk *et al.* (1979) .

In this case, the used modeling method differs greatly from the ones used in systems that are described in Figure 1. In previous systems, the model has usually been an input-output description of the controlled plant (a behavioral model of the plant), while in this case the model can be seen as a knowledge base consisting of a priori knowledge of the structure of the plant to be controlled. The knowledge base typically consists of information on delays, gains etc. which together with performance index are needed so that decisions on how to adapt the controller can be made.

A flowchart of the stages of the approach is presented in Figure 4. After measuring the performance of a process, recommended changes are generated using the model. The rule modification task determines the exact changes needed in the controller.

4. EVALUATING THE APPROACHES

To present pros and cons of different model-based approaches we have to define the kinds of goals usually set before a research or development project is launched. In actual R&D projects, the first question is usually why is the model-based approach chosen. In Chapter 2 we presented the most typical reasons to choose model-based approach. When the arguments for choosing model-based approach have been discussed, it is time to choose the structure of the model-based system. The structure must be chosen so that it fulfills the demands that have already been defined.

The structure presented in Figure 1(a) is the most simple one. The advantages of the structure are that the model and the decision maker are totally separated, which makes the maintenance of the system easy. This kind of system is quite easy to implement into any environment, as the structure makes it easy to avoid for example software engineering related problems (e.g. hard real-time demands). As mentioned already in Chapter 3.1, the problem in this kind of system is the decision maker. If we choose the control action following the flowchart in Figure 3, the simplest way to find the best possible control action is to test all possible control actions with the model. Unfortunately this is not always possible. Therefore we have to form a search or optimization algorithm to compensate for this activity. The main problem is that if we build a sophisticated search algorithm, we have to use the information applied in the model. This can make the interface between the model and the decision maker unclear, which in turn gives rise to problems in development. In the worst case, we also loose the advantages of having a separate model and decision maker. However, the presented structure seems to be a promising starting-point in many cases. With modifications and by taking the possible risks into account the structure can be utilized in many application areas.

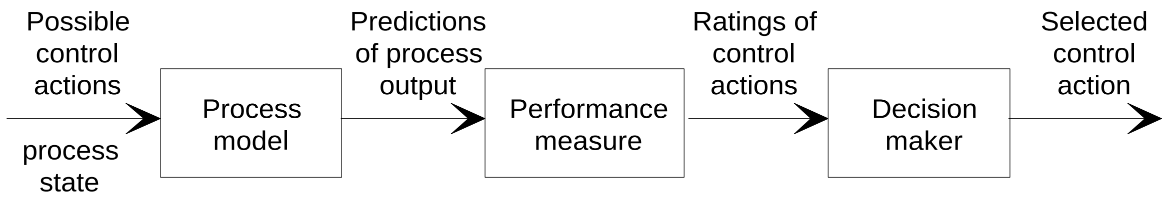

Figure 3. A flowchart of choosing control actions. Redrawn from Driankov *et al.* (1993).

The above mentioned problems can be avoided if inversion based systems (Figure 2) are used. This kind of approach is commonly used especially in traditional control systems. In principle, the optimal controller of a model is the inversion of the model. Regardless of the technique, it is often difficult to construct a very accurate model in real-world cases, which leads to the inversion based controller not being accurate. Therefore, this method should not be used when the output of the model and the process differ considerably. Additionally, it is not always possible to invert a model, or, even when it is possible, some information can be lost when inverting the model. The other problem is that further manual tuning of the control system is very difficult. Especially if the model is adapted on-line, the only way to make improvements is to improve the algorithm used in adaptation. Generally the needed inversion is quite easy to implement, and it usually does not cause any specific problems. The problems related to realization of the learning algorithm must, of course, be dealt with.

Some work has been done to avoid the need for a perfect model. Figure 5 presents the IMC (Internal Model Control) structure which can be seen as a modification of inversion based control systems. As in inversion based control systems, the controller is formed from the model in the IMC system. To handle the difference between the model and the process, the difference is used as an input in the control system. This makes the control system more robust and stable, which, in turn, makes the system attractive in cases where the perfect model is not available. In the IMC structure, it is possible to utilize different modeling techniques. Based on references, neural networks are commonly used in this area [Garcia *et al.* 1982; Hunt *et al.* 1991]

The approach presented in Figure 2 is totally different from the others. Characteristic for this approach is that learning takes place with the help of a static model based on expert knowledge. This means that the adaptation of the control system can easily be guided according to different needs, so the structure is very flexible and can therefore be applied into different environments. However, the approach as such is not very general, and it is obvious that the final structure of a control system varies from case to case because of different needs and possibilities. For example, the accuracy of expert knowledge may either encourage attempts or restrict possibilities to form up a suitable model. In our view, this approach seems very attractive. If existing expert knowledge is very uncertain, needed control system should be adaptive, the system is allowed to be highly tailored, and maintenance will not needed in future.

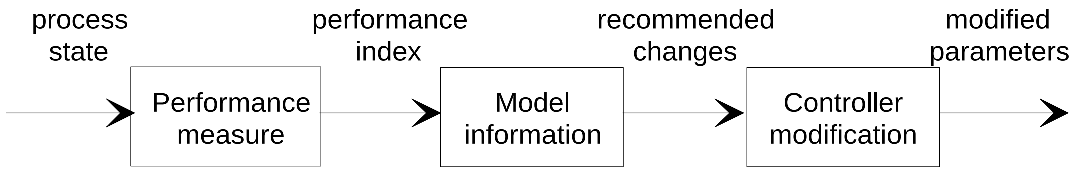

Figure 4. A flowchart of adaptation algorithm.

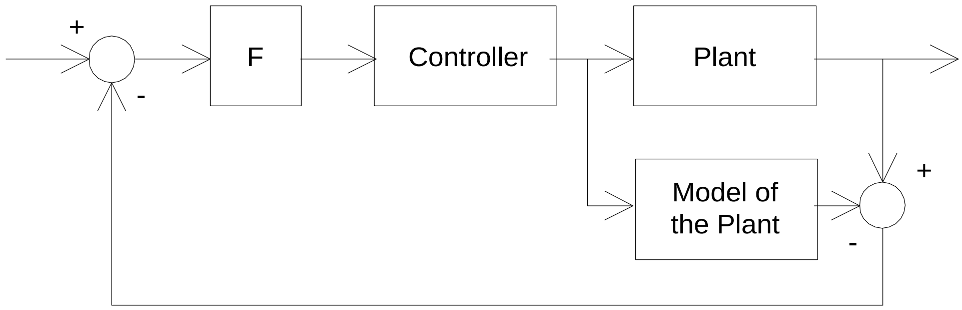

Figure 5. The IMC structure.

5. SUMMARY

When fuzzy models are used in model-based systems, there usually exist some specific advantages that are achieved by fuzzy models. Some examples of these advantages are a more accurate model and rapid development. Fuzzy models can also be used when a mathematical model is difficult to construct. The general advantages of model-based systems are functionality and maintenance related aspects. Because the model and the decision maker are separated, possible maintenance can be directed towards a specific part of the system. For example, a model can be replaced with a more accurate model in the future.

In this paper three different structures to use in model-based systems are analyzed. The basic model-based system consists a model and a decision maker. The decision maker tests different control actions to find out the best one to be used in real-process. The second approach is to use a model in developing a controller. This can be carried out by inverting the model or by using the information of the model in developing (manually) the controller. In the third approach a model is used as a part of a learning mechanism.

We evaluated several features related to model-based systems, and presented some advantages and disadvantages of different structures. In generally, one remarkable point is that how tailored a model-based systems are allowed to be? It is usually possible to develope model-based systems (as well as rule-based systems) for very specific needs, but in such cases the advantages are lost. Usually we try to devide a model-based system into functionally different parts to make, for example, the maintenance easier. In tailored systems this functionality can be difficult to maintain.

In future, the use of model-based systems will in all probability increase. In intelligent control systems different tasks will be combined. For example control, monitoring, and fault diagnosis systems can use the same model. Advantage of this kind of system is more synthesized development and maintenance. This makes model-based systems even more attractive than nowadays.

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