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The Knowledge Based Technique of Fuzzy Cognitive Maps for Modeling Complex Systems

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Abstract

Complex systems consist the majority of systems in nowadays physical and technological environment. Complex systems are very difficult to model, because of their highly nonlinear relationships demanding feedback. This paper presents Fuzzy Cognitive Maps that is a knowledge-based technique to model complex systems and handle with existing information from an abstract point of view. Fuzzy Cognitive Maps develop behavioral model of the system based on the experience and knowledge of experts. Fuzzy Cognitive Maps applicability in modeling complex systems and a hierarchical structure is proposed to model a complex system. In the hierarchical structure, Fuzzy Cognitive Map models the supervisor of the system and develops an abstract conceptual model of the complex system.

1. Introduction

The main characteristic of the real world system is the difficulty to develop precise mathematical models that may be not existent or require much of effort to be developed. It is widely accepted as the complexity of a system increases the human ability to make precise and significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance become mutually exclusive characteristics.

Complex systems are all around modern world characterized by complexity and large scale. These systems have usually high nonlinear dynamics, with variables and states strongly interrelated, with feedback cycles of influence. Conventional modeling methods have some limitations and are not well applicable to model complex systems. An approach is the investigation of new modeling methods that will integrate and combine known advanced modeling methodologies and will take under consideration the requirements for the complex systems high autonomy and intelligence. These modeling techniques will be the synergism of discipline techniques mainly based on soft computing techniques.

Especially for complex systems modeling is the basis for effective knowledge representation. On the other hand the requirements in the modeling and controlling of complex systems cannot be met only with the existing conventional methodologies and theories. This brings up the necessity to investigate and use new methods that will exploit human experience and knowledge, will have self learning capabilities, will be supplied with failure detection and identification characteristics and can handle with imprecision, uncertainty and complexity, which characterize real world systems. A very promising research area is the synergism of discipline theories: such as Fuzzy Logic, Neural Networks, Probabilistic Reasoning and Knowledge Based Systems, known as Soft Computing Techniques and/or Computational Intelligent techniques and take advantage of their strong points and develop new knowledge based models for Complex Systems. Soft Computing techniques have many advantages in modeling complex systems and processes.

Soft Computing techniques are more or less dedicated to solve particular complex real world problems using methodologies dedicated to the specific problem. Soft Computing creates a quiver of flexible tools that can perform approximate reasoning technologies that can handle information in the form of empirical prior knowledge and Input/output representing instances. Soft Computing techniques are adequate to cope with problems dealing with imprecision, uncertainty and learning and they construct simple, applicable and user-friendly models and systems.

Fuzzy Cognitive Map (FCM) is a soft computing modeling technique permitting the necessary cycles for knowledge expression within their feedback framework. FCMs originated as a combination of ideas and methods from fuzzy logic and neural networks theories. Neuro-fuzzy systems have been proposed as advanced techniques for modeling and controlling real world problems that are complex, usually imprecisely defined and require human intervention. Neuro-fuzzy systems have the ability to incorporate human knowledge and to adapt their knowledge base via optimization techniques. They can play an important role in the conception, description and modeling complex systems [Lin and Lee, 1996].

Fuzzy Cognitive Map (FCM) has appeared as a synergism of Fuzzy Logic, Neural Networks and knowledge representation techniques. FCM is a connectionist network of concepts that can be used to model situations by classes and their causal links between them. FCM is an unrestricted network, their nodes are the problem domain concepts and the weighted interconnections present the causal interaction degree. FCMs illustrate the causal relationship between different factors, where either positive or negative sign of knowledge are session describing with a fuzzy weight expresses the causal relationship. FCM have no restriction on the graph complexity.

Causal and cognitive maps have been used to describe decision-based systems and then they were supplied with fuzzy logic theory enhancing Cognitive Maps ability to present and model qualitatively dynamic systems [Kosko, 1986]. Cognitive Maps have been used to make decision analysis and cooperate distributing agents [Zhang *et al.*, 1992]. Many researchers have been attracted by the FCM potential [Dickerson and Kosko, 1994] and they proposed new FCM models and new methods for developing FCM [Craiger *et al.*, 1996; Stylios and Groumpos, 2000]. Fuzzy values considered in cognitive maps and FCMs were used to represent causal reasoning and inference [Miao and Liu, 2000]. FCMs have proposed to represent complex social systems where relationship between social forces demands feedback [Taber, 1991, 1994]. Fuzzy Cognitive Map used to model and support plant control systems and perform Failure Modes and Effects Analysis in the process industry [Pelaez and Bowles, 1996]. Another investigation concerns hierarchical systems, where supervisor incorporates knowledge and is capable of learning relational structures and evidential reasoning and modeling the Supervisor of control systems [Stylios and Groumpos, 1999].

This paper focuses on the use of Fuzzy Cognitive Maps to model and represent knowledge for dynamical complex systems. FCMs can handle with the qualitative and quantitative data and have the potential to model any dynamic real world system with feedback. It presents a general overview of FCM and a developing methodology is proposed. Some interesting results for the usage of Fuzzy Cognitive Maps in modeling complex systems are come up and are discussed.

2. FUZZY COGNITIVE MAPS

Fuzzy Cognitive Maps are conceptual models that are developed by human experts who have knowledge and experience in the operation and behavior of the system. Experts design a fuzzy graph structure of the system, consisting of concepts-nodes that represent the key principles - functions of the system's operation and behavior. The fuzzy weighted arcs between concepts that show the fuzzy degree of causation with which each concept influences others depict the interrelationships among concepts. The causal knowledge is stored on the interconnections that summarize the correlation between cause and effect among concepts.

Fuzzy Cognitive Maps are constructed either by experts or based on presenting knowledge in the form of literature. FCM is a knowledge-based system as it utilizes the knowledge and experience of experts to be developed. It is accepted that the perceptions of experts create a subjective rather than objective world and model of the system. The main concern is to describe which element of the system influences which other and the degree of this influence. There is an inference mechanism that describes the relations among elements as fuzzy causal relationships. Different values of influence are recommended and accepted; this is the main strength of this method. FCMs are ideal for knowledge and conceptual representation of complex systems in a soft way where the concepts of the system and their relationships are mainly fuzzy and not precisely estimated.

FCM illustration is an interactive structure of nodes that stand for the concept of the system and are interconnected with weighted arrows that indicate the direction of the influence and the weight is the numerical transformation of the fuzzy causal relationship among concepts.

The graphical illustration of FCM is a signed directed graph with feedback, consisting of nodes and weighted arcs. Nodes of the graph stand for the concepts that are used to describe the behavior of the system and they are connected by signed and weighted arcs representing the causal relationships that exist between the concepts (Figure 1). All the values in the graph are fuzzy, so concepts take values in the range between [0,1] and the weights of the arcs are in the interval [-1,1].

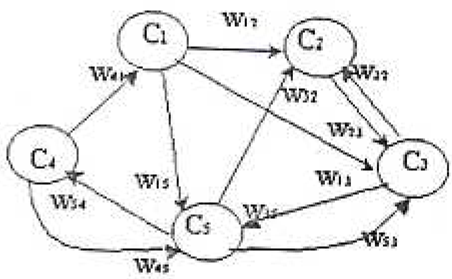

Figure 1. The Fuzzy Cognitive Map model

The Fuzzy Cognitive Map consists of nodes-concepts and arcs between concepts. Each concept represents a characteristic of the system; in general it stands for states, variables, inputs, events, actions, goals, values, trends of the system that is modeled as an FCM. Each concept is characterized by a number A_i that represents its value and it results from the transformation of the fuzzy real value of the system's variable, for which this concept stands, in the interval [-1,1].

Between concepts, there are three possible types of causal relationships, that express the type of influence from one concept to the others. The weights of the arcs between concept C_i and concept C_j could be positive ($W_{ij} \succ 0$) which means that an increase in the value of concept C_i leads to the increase of the value of concept C_j, and a decrease in the value of concept C_i leads to the decrease of the value of concept C_j. Or there is negative causality ($W_{ij} \prec 0$) which means that an increase in the value of concept C_i leads to the decrease of the value of concept C_j and vice versa.

Experts design and develop the fuzzy graph structure of the system, consisting of concepts-nodes that represent the key principles-factors-functions of the system operation and behavior. Fuzzy Cognitive Maps describes the perception of experts about the system. Then, experts determine the structure and the interconnections of the network using fuzzy conditional statements. Experts concern to describe whether the states of one concept influence the state of another. Cause and effect relations among concepts are the basis of expectations and it is important in every system trying to model and replicate brain like intelligence. Experts use linguistic variables in order to describe the relationship among concept, and then all the linguistic variables are combined and so the weights of the causal interconnections among concepts are concluded. The simplest FCMs act as asymmetrical networks of threshold or continuous concepts and converge to an equilibrium point or limit cycles. At this level, they differ from Neural Networks in the way they are developed as they are based on extracting knowledge from experts. FCMs have non-linear structure of their concepts and differ in their global feedback dynamics.

The value A_i for each concept C_i is calculated by the following rule:

$$A_i = f\left(\sum_{\substack{j=1 \\ j \neq i}}^{n} A_j^{t-1} W_{ji} + A_i^{t-1}\right) \qquad (1)$$

Namely, A_i is the value of concept C_i at time t, A_i^{t-1} the value of concept C_i at time $t-1$, A_j^{t-1} the value of concept C_j at time $t-1$, and the weight W_{ji} of the interconnection from concept C_j to concept C_i and f is a threshold function.

The unipolar sigmoid function is the most used threshold function, [Lin and Lee, 1996] where $\lambda \succ 0$ determines the steepness of the continuous function f. The sigmoid function ensures that the calculated value of each concept will belong to the interval [0,1].

$$f(x) = \frac{1}{1+e^{-\lambda x}} \qquad (2)$$

Given two events that are represented by two concept A and B in FCM terms, the main question that have to be answered is

i) Does event A cause B or vice versa?

ii) What is the strength of the causal relationship?

Causality plays a key role in knowledge-based systems. The issue of how to understand and learn the existing cause and effect relations is central to any effort achieve human like intelligence. The main problems concerning causality in that context are the discovery of causal knowledge, its representation and its use. In the general common approach, causal information emerges from statistical data, by looking at data that occur simultaneously, but it is clear that the co occurrence of data does not always mean that the data are causally linked. The proposed approach utilizes the knowledge and experience of experts asking them to describe the existing causal relationship using Fuzzy rules.

The causal information is not directly used for reasoning in the framework of Fuzzy Cognitive Map models of knowledge-based systems. In this case the notion of causality occurs when a user has to build, to represent and to exploit a knowledge-based system.

FCM dynamics depend on the dynamics of the concept nodes and causal edges. These adaptive feedback fuzzy systems are nonlinear function approximations with even more complex dynamics than feedback neural networks [Kosko, 1997].

3. Complex Systems and Fuzzy Cognitive Maps

Modern systems become more complex and highly sophisticated, they are characterized by highly nonlinear dynamics that couple a variety of physical phenomena in the temporal and spatial domains. For such systems intelligent fuzzy logic based techniques and object modeling are proposed to address uncertainty issues and provide flexible platforms. It is not surprising, therefore, that much of these processes are not well understood and their operation is "tuned" by experience rather than through the application of scientific principles. Capturing and utilizing the expert's knowledge, effectively and efficiently, promises to improve plant operational conditions. Usually operators of the system observe multiple data simultaneously and they make tough decisions based on their experience and empirical knowledge [Jamshidi, 1983].

Complex systems operate in changeable and unknown environment, as the factors that influence the system and determine their behavior cannot be easily determined. Especially, when environment changes, system has to adapt and the input-output characteristics of the system have to be altered. If a single model is identified, it will have to adapt itself to the new environment. In non-linear systems, a single model may not be adequate to identify changes in the process behavior (i.e., a model may not exist in the assumed framework to match the environment). Hence, multiple models could be used to identify the different environments. In some environments different models may be available whose validity (or accuracy) depends upon the region in the state space where the system trajectories lie. All the above considerations suggest that multiple models may be preferable to a single model, in many different situations.

A general accepted method is the analyzing into subsystems. Each subsystem is consisted of the most strongly coupled components and the subsystems themselves depend each other. A set of separate models is used to form hybrid models. The rationale for using multiple models is to ensure that there is at least one model with parameters sufficiently close to those of the unknown process. This multiple models approach possesses different modeling strategies to accommodate different operating conditions, adaptive behavior to perform model design under uncertain or unfamiliar situations and the capability to co-ordinate separate models to accomplish the overall system task.

Fuzzy Cognitive Maps (FCMs) use a symbolic representation for the description and modeling of systems; it is consisted of concepts and illustrates different aspects in the behavior of the system and these concepts interact with each other showing the dynamics of the system. An FCM integrates the accumulated experience and knowledge on the operation of the system, as a result of the method by which it is constructed, i.e., using human experts that know the operation of system and its behavior. They represent the human accumulated knowledge on the operation and behavior of the system, using concepts to stand for each characteristic of the system. Experts are actively involved in the creation of models and they interact with the models and so their understanding for the benefits of models will increase the quality of models, the inherent knowledge in the model will be used more frequently and models will be widely accepted.

Fuzzy Cognitive Maps are proposed to aggregate the separate models playing the role of supervisor-selector among different models. An augmented Fuzzy Cognitive Map can accomplish identification of the process models and cope with limited uncertainty situations. It may comprise different models, identification and estimation algorithms. Fuzzy Cognitive Maps are used to aggregate the set of different modeling technologies. It must be mentioned that each one models has its one state space and there is a partially overlapping between the state spaces. For specific operational conditions or input/output conditions one model may be more suitable to be used and this model control better the system. The selection between different models is based on operational characteristics and different factors. Figure 2 illustrates an augmented Fuzzy Cognitive Map, which aggregates four different models of the system. The simulation of this FCM will lead to selection of one model using a winner take all method. Between factors and models there is feedback and there must be a number of repetition of running the FCM, in order the concept-models to reach their final values. When after a certain number of repetitions e.g. 8 repetitions equilibrium has been reached and the values of concepts-models no longer change, the procedure stops and the final values of concepts-models are found, the maximum of which will be the most suitable model. Fuzzy Cognitive Maps base their selection of different models in evaluating the influence of each factor to each model in a similar way that a human operator does. FCMs best utilize existing experience in the operation of the system and are capable in modeling the behavior of complex systems using discipline models.

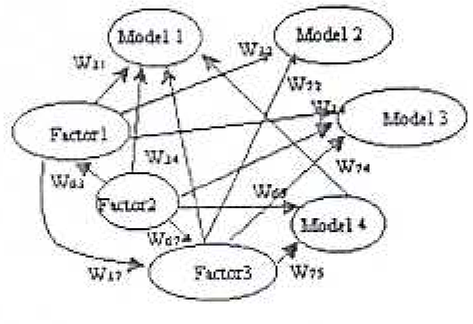

Figure 2 The supervisor FCM multi-model

It is suggested a hierarchical structure where Fuzzy Cognitive Map is proposed to model the supervisor. FCM is used as a selector of the appropriate model among different models for the complex system. It is supposed that the complex system has been decomposed in subsystems and for each subsystem the corresponding Fuzzy Cognitive Map model has been constructed. The scheme of this structure is depicted in figure 3, where the supervisor FCM is an augmented model of the complex system and it represents the relationships among the subsystems and their models. This two-level hierarchical structure is used to model a complex system.

The supervisor is used for more generic purposes; to organize all the subsystems in order to accomplish a task, to help the operator make decisions, to planning strategically and to detect and analyze failure. This supervisor will give priority to different subsystem-model each taking into consideration some factors and will determine the degree with which every subsystem-model is active every time and participate in the whole complex system. The main supervisory control task is the co-coordinating of the whole plant. It supervises the production, co-ordinates the sharing of the resources, it schedules the production, choosing between different production sequences and the right command to the right agent. Role of the FCM is to extend the range of application of a conventional controller by using a more abstract representation of the process, general control knowledge and adaptation heuristics and to enhance the performance of the whole complex system.

Supervisor FCM includes advanced features such as fault diagnosis, effect and cause analyses [Pelaez and Bowles, 1995] prediction capabilities, decision analysis, and strategic planning. The construction of the supervisor Fuzzy Cognitive Map will be based on the expert's heuristic knowledge about the whole systems Moreover, this FCM will include concepts for description and determination of a specific operation of the system, or other qualitative preferences for the planning and scheduling of the process. To draw and develop this FCM, the integration of several expert opinions will be needed.

In the lower level, the role of FCM is to extend the range of application of a conventional controller by using more abstract representation of process and general control knowledge and adaptation heuristics and enhance the performance of the whole system. Thus FCM may replicate some of the knowledge and skills of the control engineer. FCM is built using a combination of the knowledge representation techniques as causal models, production rules and object hierarchies and it is used to perform more demanding procedure as failure detection, decision making, planning, tasks usually performed by a human supervisor of the controlled process.

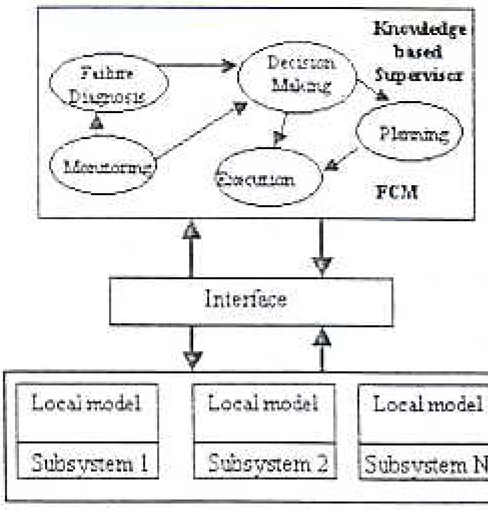

Figure 3. The two level hierarchical model of complex system consisting of submodels and the supervisor model.

The introducing of multiple models structure is a prospective way to improve the current estimation of plant behavior. For the sophisticated plants with immeasurable or hard measurable variables and large uncertainties the scheme using multiple separate models received by aggregation of different modeling techniques is an efficient approach in model design. An augmented Fuzzy Cognitive Map can accomplish identification of the process models and cope with limited uncertainty situations. It may comprise different models, identification and estimation algorithms. It can perform a kind of maintenance of the system by integrating alternative modeling methods.

4. CONCLUSIONS

The soft computing modeling methodology of Fuzzy Cognitive Maps, which have been reviewed and presented in this paper, offer tremendous opportunities for design and implementation of new models for complex systems. Taking advantage of this unique opportunity is the main issue that needs to be addressed. The increasing in the complexity and sophistication of complex systems requires the implementation of new soft computing techniques to develop intelligent systems. Human expert has a key role in the supervision of complex systems. Capturing the heuristic knowledge of experts, representing, modeling and exploiting it using FCMs may provide the foundation of new directions in modeling and controlling complex systems.

The proposed FCMs methodology to knowledge engineering has many advantages over the alternatives. FCM can represent complex causal relationships. FCM models the supervisor of complex system directly from experts who have knowledge on the behavior of the system. The primary attention is paid to the human's behavior and experience, rather than to the system being described. This distinctive feature makes Fuzzy Cognitive Maps applicable and attractive for dealing with the supervised problem where the system on the lower level is complex but it can be supervised and controlled satisfactory by human operators.

Human operator using imprecise and control methodology monitors and controls complex systems. Required characteristics of complex systems are the possession of human-like expertise within a specific domain, adaptation themselves and learning to do better in changing environments. Fuzzy Cognitive Maps is a symbolic representation for the description and modeling of complex systems, describing different aspects in the behavior of complex systems in terms of concepts; and interactions among concepts show the dynamics of a system. A hierarchical structure is proposed following the principle of "decreasing precision and increasing intelligence" [Saridis, 1989] where the supervisor of complex systems is modeled as a Fuzzy Cognitive Map.

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