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FUZZY COGNITIVE MAPS MODELLING SUPERVISORY LARGE SCALE CONTROL SYSTEMS

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Abstract: This paper investigates the implementation of a hybrid methodology, which combines fuzzy logic and neural networks, Fuzzy Cognitive Map (FCM), for the modeling of the supervisor of Large Scale Systems. The description and the construction of Fuzzy Cognitive Map will be extensively examined and it will be proposed a model for the supervisor. There is an oncoming need for more autonomous and intelligent systems, especially in Large Scale Systems and the application of Fuzzy Cognitive Map for the modeling of the Supervisor may contribute in the development of more autonomous systems.

Keywords: Modeling, Supervisory Control, Cognitive Systems

1. INTRODUCTION

Modern systems are characterized as large-scale systems with a variety of variables and factors. For complex dynamical systems, conventional methods have a limited contribution in modeling and controlling such systems. New methods are proposed for complex systems, which will utilize existence knowledge, human experience, will have learning capabilities and will have advanced characteristics such as failure detection and identification qualities. In this paper a new methodology, Fuzzy Cognitive Map (FCM), is proposed for modeling systems which may contribute to the effort for more intelligent control methods. A Fuzzy Cognitive Map draws a causal picture to represent the model and behavior of system, within this representation, concepts of FCM interact according to imprecise rules and the operation of the complex large scale system is simulated.

Fuzzy Cognitive Map is a symbolic representation of the description and modeling of the system. It consists of concepts, that illustrate different aspects in the behavior of the system and these concepts interact each other showing the dynamics of the system (Kosko, 1986). The human experience and knowledge on the operation of the system is behind a Fuzzy Cognitive Map, 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 in different circumstances. FCMs describe the behavior of a system in terms of concepts, each concept represents a state or a characteristic of the system (Dickerson and Kosko, 1994). FCMs illustrate the whole system by a graph showing the cause and effect along concepts, and are a simple way to describe the system's behavior in a symbolic manner, exploiting the accumulated knowledge of the system.

Fuzzy Cognitive Map (FCM) Theory, the methods that it uses to describe and model the behavior of a system and its application in the modeling the supervisor of large-scale systems are examined. (Stylios, *et al*., 1997). Fuzzy Cognitive Maps have been used for decision analysis, management science and operations research (Craiger, *et al*., 1996). The objective here is to focus on the use of FCM in modeling systems and show how appropriate FCMs are to exploit the knowledge and experience which has been accumulated for years on the operation of a complex plant. These technologies are crude analogs of systems that exist in human and animal systems and have their origins in behavioral phenomena related to these beings (Medsker, 1995). So, FCM represents knowledge in a symbolic manner and relates states, events and inputs in an analogous to beings manner. This methodology could help human intention to construct more intelligent systems, since as the more intelligent a system becomes, the more symbolic and fuzzy a representation it utilizes.

2. FUZZY COGNITIVE MAPS

Fuzzy Cognitive Maps (FCM) is a new modeling methodology for complex systems, which originated from the combination of Fuzzy Logic and Neural Networks. 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 main behavioral characteristics of the system and they are connected by signed and weighted arcs representing the causal relationships that exist among concepts (Figure 1). Graphical model of FCM is so simply that with inspection, it becomes clear which concept influences other concepts showing the interconnections between concepts

2.1 Fuzzy Cognitive Map representation

Each concept represents a characteristic of the system; in general it stands for 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 real value of the system's variable, for which this concept stands, in the interval [0,1]. It must be mentioned that all the values in the graph are fuzzy. Causality between concepts allows degrees of causality and not the usual binary logic, so the weights of the interconnections belong to the interval [-1,1] (Kim, 1998). Fuzzy Cognitive Map describes a system in a one-layer network whose nodes can be assigned concept meanings and the interconnection weights represent relationships between these concepts. FCMs are fuzzy-graph structures, which are analogous to unsupervised modes of Neural Networks.

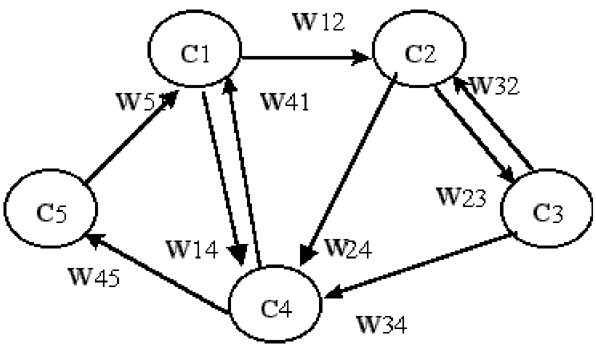

Fig.1. A simple Fuzzy Cognitive Map.

A Fuzzy Cognitive Map is an oriented graph which shows the degree of causal relationship between different factors, where knowledge expressions, in the causal relationship, are expressed by either positive or negative sign and different weights. A fuzzy cognitive map can avoid many of the knowledge-extraction problems which are usually posed by rule based systems. It must be mentioned that cycles in the graph are allowed.

Fuzzy Cognitive Maps are used to model the knowledge base of the examined system. FCM stores knowledge in the nodes and edges of the network, each node-concept represents one of the key-factors of the modeled system. Relationships between concepts have three possible types; either express positive causality between two concepts ($W_{ij}>0$) or negative causality ($W_{ij}<0$) or no relationship ($W_{ij}=0$). The value of W_{ij} indicates how strongly concept C_i influences concept C_j. The sign of W_{ij} indicates whether the relationship between concepts C_i and C_j is direct or inverse. The direction of causality indicates whether concept C_i causes concept C_j, or vice versa. These parameters have to be considered when a value is assigned to W_{ij}.

The simplicity of the FCM model becomes apparent from its mathematical representation and operation, which evoke an inference. So, an FCM, which consists of n concepts, is represented mathematically by a $1\times n$ state vector $\mathbf{A}$, which gathers the values of the n concepts and by an $n\times n$ edge matrix $\mathbf{W}$. The matrix $\mathbf{W}$ is n by n, and each element e_{ij} of the matrix indicates the value of the weight W_{ij} between concept C_i and C_j and the matrix diagonal is zero since it is assumed that no concept causes itself.

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

$$A_i^t = c f\Big(\sum_{\substack{j=1 \\ j\neq i}}^{n} A_j^{t-1} W_{ji}\Big) + A_i^{t-1} \tag{1}$$

Namely, A_i^t is the value of concept C_i at time t, A_j^{t-1} is the value of concept C_j at time t-1, A_i^{t-1} is the value of concept C_i at time t-1, and W_{ji} is the weight arc from C_j to C_i and f is a threshold function, usually the sigmoid is used which squashes the result in the interval [0,1]. The nonnegative parameter c represents the fraction of the summed multiplication, which is added to the previous value of each concept. This parameter can be in the range $0.01 \le c \le 0.1$. It is assumed that Fuzzy Cognitive Map had discrete nature. At the same time unit, values of all concepts are recalculated and change according to equation 1. This procedure is called a cycle of FCM.

So the new state vector $\mathbf{A}$ at time t, which is computed by multiplying the previous state vector $\mathbf{A}^{t-1}$ time t-1, by the edge matrix $\mathbf{W}$, plus the old state vector.

$$\mathbf{A} = cf(\mathbf{A}^{t-1}.\mathbf{W}) + \mathbf{A}^{t-1} \tag{2}$$

2.2 Methods for construction Fuzzy Cognitive Maps

The development and construction of Fuzzy Cognitive Map have great importance for the modeling of the system. Proposed methodologies rely on the exploitation of experts' experience on system's model and behavior. So an expert draws a FCM according to his experience, he determines the concepts, which in general stand for events, actions, goals, values, and trends of the system. Moreover he determines the negative or positive effect of one concept on the others, with a fuzzy degree of causation. In this way, an expert decodes his own knowledge on the behavioral model of the system and transforms this knowledge in a weighted graph.

In order to construct a better model of the system, the experience of a group of experts can be utilized. They are polled together to determine the relevant factors that should be present in the map. So, they decide the number of nodes from which map is consisted of and what characteristic of the system each node represent (Schneider, *et al*., 1998). Then, the experts are individually asked to express the relationship among these factors. In this way there will be a collection of individual FCMs, with the same nodes but different links among concepts or/and different weights of interconnections that must be combined into one collective map. So, what is needed is a method to combine the individual maps. A first approach could be the summation of different weight matrix:

$$\mathbf{W} = f\left(\sum_{1}^{N} \mathbf{W}_i\right) \tag{3}$$

Where $\mathbf{W}$ is the overall matrix, $\mathbf{W}_i$ is the individual weight matrix, which each one of the N experts has developed, and f is a threshold function, usually the appropriate sigmoid is used to ensure that weights of the overall map belong to the interval [-1,1].

It is common that not all experts have the same experience and knowledge on the system. It could be considered that there are experts of different credibility on the knowledge of the system, and for these experts their constructions may be multiplied by a nonnegative 'credibility' weight b_i before combining them with other expert's opinions.

$$\mathbf{W} = f\left(\sum_{1}^{N} b_i \mathbf{W}_i\right) \tag{4}$$

Where b_i is the credibility weight for i_{th} expert and $\mathbf{W}_i$ is the weight matrix of i_{th} expert's fuzzy cognitive map and N is the number of the experts. But in this case, another mechanism must be used to determine who and how credibility weights will be assigned to every expert. Or one expert could be "penalized" with an extremely low or zero credibility weight if the expert's choice is extremely different than other experts' weight choice.

Equations 3 and 4 are based on summation, in order to integrate individual matrices into one augmented Fuzzy Cognitive Map. Other mathematical operations that could be used, are the min and max operations. Another mathematical approach for the choice of the suitable weights, which do not need to assign credibility weights for experts, follows.

Every expert constructs an individual FCM. Then different weights from each individual map for each one interconnection are collected together and they form an area on the 2-dimension space. As an example the weights, which six different experts have suggested for one connection, are:

wij=[0.5, 0.6, 0.66, 0.7, 0.65, 0.1].

The weight suggested by the 6^{th} expert with value 0.1 is excluded from the calculation. And the rest of the weights are used to find the center of this area. In this case, the chosen weight has the value 0.62 for this particular weight interconnection. The same methodology is used to assign weights for all the interconnections of the final FCM.

Another methodology to construct a Fuzzy Cognitive Map that is closer to techniques of fuzzy systems is presented. Experts are asked to describe the causality among concepts using linguistic notions. They will describe influence of one concept to the other as "very strong", "strong", "medium", "weak", "zero" and "negative" or positive". Then, these linguistic variables for each interconnection can be combined and a fuzzy set will be computed, as fuzzy logic theory suggests (Nie and Linkens, 1995). After, this procedure, linguist variables will be transformed with the use of membership functions to numerical ones, in the interval [-1,1]. This methodology has the advantage that experts do not have to assign numerical causality weights but to describe the degree of causality among concepts.

Different methodologies for the assignment weights to Fuzzy Cognitive Map have described, with the assumption that all experts develop the same FCM with the same nodes but different interconnections. A similar methodology could be used to integrate different Fuzzy Cognitive Maps, which consist of different nodes, in one augmented FCM. If there is a distributed system, for each subsystem a distinct FCM is constructed and then all FCMs could be combined in one augmented matrix $\mathbf{W}$ for the whole system. The unification of the distinct FCM depends on the concepts of the segmental FCM, if there are no common concepts among different maps, the combined matrix $\mathbf{W}$ is constructed according to the equation 5. In this case, there are K different FCM matrices, with weight matrices $\mathbf{W}_i$ and the dimension of matrix $\mathbf{W}$ is $n \times n$ where n equals the total number of distinct concepts in all the FCMs.

$$\mathbf{W} = \begin{bmatrix} \mathbf{W}_1 & & & \\ & \mathbf{W}_2 & \underline{0} & \\ & \underline{0} & \ddots & \\ & & & \mathbf{W}_K \end{bmatrix} \qquad (5)$$

But, in most cases, the unification is used because there are common concepts among the distinct FCM and the intention is the construction of an integrated Fuzzy Cognitive Map. In this case, some of the non-diagonal elements of matrix $\mathbf{W}$ in equation 5 are nonzero, which represent the interconnection between concepts that belong to different FCMs. Then, segmental FCMs with common concepts, are combined together, calculating new weights for the interconnection between common concepts, these weights are determined with one of the previously described methodologies for the choice of weights when each expert suggest a different one. Then, equation 5 is implemented to construct the weight matrix of the overall Fuzzy Cognitive Map which is consisted of n concepts that correspond to the total number of the different concepts that have been present in all the segmental FCMs.

2.3 Neural network nature of Fuzzy Cognitive Maps

Fuzzy Cognitive Maps have been described as a hybrid methodology, which utilizes characteristics of fuzzy logic and neural networks. The development and construction of FCMs shows their fuzzy nature. Learning rules can be borrowed of the Neural Networks theory and to use them to train the Fuzzy Cognitive Map. Parameter learning of FCM will concern the updating of connection weights among concepts.

The described construction of FCM is based on experts who determine concepts and weighted interconnections among concepts. This methodology would lead to a distorted model of the system. In order to refine the model of the system, learning rules are used to adjust weights of FCM interconnections. The Differential Hebbian learning rule has been proposed (Kosko, 1992) to be used in the training of a specific type of FCMs. The Differential Hebbian learning law adjusts the weights of the interconnection between concepts, it grows a positive edge between two concepts if they both increase or both decrease and it grows a negative edge if values of concepts move in opposite directions. Moreover, it is an unsupervised method and thus, its computational load is light.

Appropriate learning rules for Fuzzy Cognitive Maps need more investigation. These rules will give FCMs some useful characteristics of Neural Networks such as the ability to learn arbitrary non-linear mappings, capability to generalize to situations that are different from the training data, their adaptivity and their fault tolerance capability (Jang, *et al*, 1997).

3. FEATURES OF FCM FOR SUPERVISORY CONTROL SYSTEMS PROBLEMS

Large Scale systems are complex systems, characterized with high dimension and their model is nonlinearly interconnected with uncertain information flow such that classical control techniques cannot easily handle the system. The application of Fuzzy Cognitive Maps in this kind of systems for the modeling of the supervisor of the whole system seems to be a prospective methodology. For the large-scale complex systems model, the hierarchical structure of figure 2 is proposed. In the lower level of the structure will lie the plant, which is controlled through conventional controllers. These controllers perform the usual tasks and reflect the model of the plant during normal operation conditions. The supervisor of the system is modeled as a Fuzzy Cognitive Map, which will be used for failure modes, effects analysis (Pelaez and Bowles, 1996).

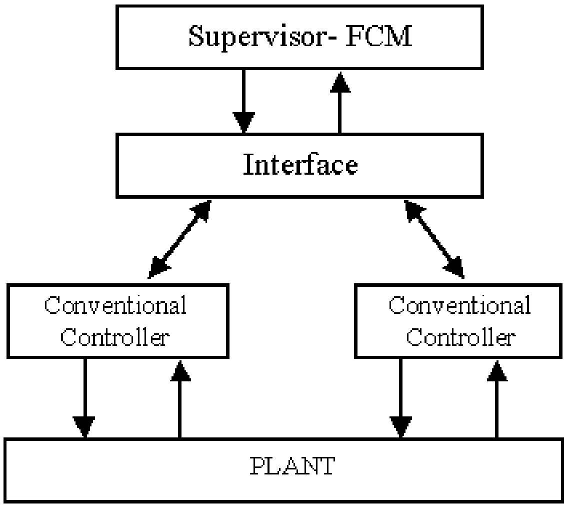

Fig.2. Hierarchical structure for supervisor control

There is an amount of information that must pass from the lower level to the Supervisor-FCM. So an interface is needed, which will filter, transform and pass information from the local controllers to the FCM on the upper level. Then Fuzzy Cognitive Map will interact using equation 1; concepts of FCM will have new values that must be transmitted to the conventional controllers. So, the interface must work in the opposite direction, so that it is possible that changes on two or more concepts in the FCM could mean change in one or more factors on controllers.

With Fuzzy Cognitive Maps the knowledge and human operator experience is exploited. The human coordinator of a system knows the operation of a whole system and has it stored in his mind in terms of concepts. He relates the operation of one subsystem or two different subsystems to a concept, or a concept stand for a specific procedure.

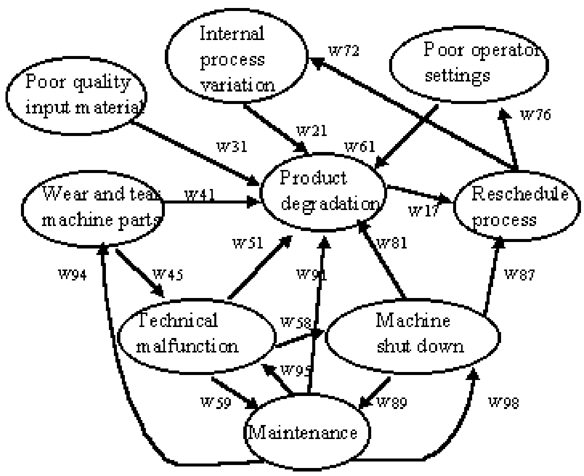

Fig.3. Proposed Fuzzy Cognitive Map for a process

The FCM will consist of concepts that may represent the irregular operation of some elements of the system, failure mode variables, failure effects variables, failure cause variables, severity of the effect or design variables. Moreover, this FCM will include concepts for determination of a specific operation of the system. This FCM may be used for failure modes, effect analysis and strategic planning, decision analysis. In this FCM analysis of the data coming from the lower level can be implemented, which will represent vital components of the plant detecting features that reflect the operational state of the plant. For drawing this FCM the integration of several expert opinions will be needed in order to achieve its diagnosis and predictive task, which is extremely difficult.

Different experts were asked to develop a Fuzzy Cognitive Map, which would describe the operation of a process, the final product of the process and the different aspects that determine the quality of the product. They developed the FCM of the figure 3, where concept C1, represents “product degradation”. This concept depends on concept C2 “the internal variation of the process”, concept C3 “the poor quality of the input material”, concept C4 “wear and tear machine parts”, concept C5 “technical malfunction”, concept C6 “poor operator settings”, concept C8 “machine shut down”. The “degradation of product” causes positively concept C7 “rescheduling process” and concept C7 decrease the value of concepts C6 “poor operator setting” and concept C2 “Internal process variation”. Concept C4 “wear and tear machine parts” influences concept C5 “technical malfunction”, which increase concept C9 “the maintenance” and the amount of concept C8 “the machine shut down”. Concept C9 “maintenance” decreases C5 “technical malfunction”, C8 “the machine shut down” and concept C4 “wear and tear machine parts”. Concept C8 “machine shut down” causes concept C7 “reschedule process” and increases the value of concept C9 “maintenance”.

When the FCM was developed, experts were asked to assign values on the interconnections among concepts. So, FCM of figure 4 was constructed.

For the constructed Fuzzy Cognitive Map, values were assigned to the concepts and the simulation of the FCM was started. Equation 1 was used to calculate the new values of concepts after each step of the FCM. Table 1 gathers the initial values of concepts and their values for five simulation cycles. FCM reaches an equilibrium point and if a new value for one or more concepts come from the lower level then after a limited number of cycles, FCM will reach another equilibrium point.

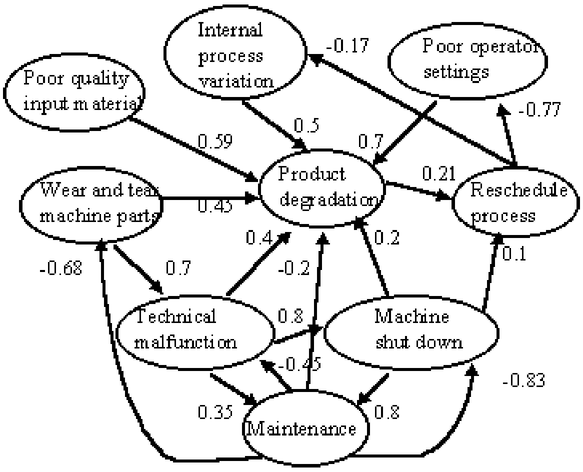

Fig.4. Fuzzy Cognitive Map with weights.

Table 1 Values of concepts for five steps

C1	C2	C3	C4	C5	C6	C7	C8	C9
0.24	0.48	0.20	0.10	0.15	0.40	0.00	0.07	0.61
0.65	0.50	0.20	0.40	0.45	0.50	0.51	0.40	0.53
0.74	0.48	0.20	0.41	0.51	0.40	0.54	0.48	0.62
0.73	0.48	0.20	0.40	0.50	0.40	0.55	0.47	0.64
0.72	0.48	0.20	0.39	0.50	0.40	0.55	0.47	0.64

Figure 4 depicts a Fuzzy Cognitive Map, which is used as supervisor of the plant. The development of the supervisor-FCM dedicated to a particular plant depends on the supervisory-coordinator tasks that are required by the user of overall system. This is not a complete Fuzzy Cognitive Map, which would include a decision making part and a planning part.

4. SUMMARY

Fuzzy Cognitive Map Theory, a new theory used to model the behavior of complex systems, which best utilizes existing experience in the operation of the system, has been examined. For such systems it is extremely difficult to describe the entire system by a precise mathematical model. Thus, it is more attractive and useful to divide the whole plant in virtual parts and to construct an FCM for each part. The experience of different specialists who can easily judge the variables and states of a small process and then unify these to construct the final system by integrating the different Fuzzy Cognitive Maps into an augmented one can be utilized for each part, as was described previously in this paper. This approach represents systems in a graphical way showing the causal relationships between states-concepts and accomplishes the unification of knowledge by superposing many small systems. It offers the opportunity to produce better knowledge based system applications, addressing the need to handle uncertainties and inaccuracies associated with real world problems.

An example of an FCM for supervisory control systems was developed which consisted of concepts that may represent the irregular operation of some elements of the system, failure mode variables, failure effects variables, failure cause variables, severity of the effect or design variables. In the development of this FCM the integration of several expert opinions was included in order to achieve its diagnosis and predictive task and the results after five simulation steps were shown.

FCMs are a type of symbolic methodology, which can increase the effectiveness, autonomy and intelligence of systems. Since this symbolic method of modeling and control of a system is easily adaptable and relies on human expert experience and knowledge it can in a sense be considered intelligent.

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