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Ali Bahrami
Missouri University of Science and Technology, bahramia@mst.edu

Cihan H. Dagli
Missouri University of Science and Technology, dagli@mst.edu

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Ali Bahrami[†‡], Cihan H. Dagli[†‡], Batoul Modarress[*]

[†]Intelligent Systems Center
School of Engineering, University of Missouri-Rolla
Rolla, Missouri, 65401

[‡]Department of Engineering Management
University of Missouri-Rolla
Rolla, Missouri, 65401

[*]Boeing Commercial Airplane Group
P.O.BOX 3707 MS 74-40
Seattle, Washington, 98124-2270

Abstract

The need to automate the design process has generated a variety of software packages such as Computer Aided Design and Manufacturing (CAD/CAM), Computer Aided System Engineering (CASE) and others that have become conventional engineering tools. Although these tools can greatly enhance the detailed aspects of design such as analysis of the final design or drafting, they are nevertheless incapable of aiding designers during the conceptual or creative phase of the design process. This paper examines the feasibility of utilizing Fuzzy Associative Memory (FAM) in conceptual design and illustrates the concept by applying it to the idea generation phase of design activity.

1. Introduction and Motivation

Design is a highly knowledge intensive activity. The more knowledge and experience the designers have the better are the chances for generating creative design. Design involves continuous interplay between what we want to achieve and how we want to achieve it [8]. A designer usually associates sets of fuzzy functional requirements with sets of physical structures, then during the design process, design solutions are retrieved from memory to solve the design problem. Nam Suh defines the design as a mapping process from the functional space to the physical space in order to satisfy the designed-specified functional requirements, see Equation 1 (Suh, 1984; Suh et al., 1978, 1979) [8].

$$D : FRs \rightarrow DPs \qquad (1)$$
$$FR_i = \sum_j A_{ij} DP_j$$
$$A_{ij} = \frac{\partial FR_i}{\partial DP_j}$$

Where FR_i is the functional requirement and DP_j is the design parameter. Major difficulty in Suh's paradigm is in defining the mathematical functions of multi-variables for the functional requirements and derivation of the design matrix A, which is needed for the mapping process.

Most of the practical problems we face in the design are either too complex or too ill-defined to analyze with conventional approaches. In order to come up with a manageable set of data, we may ignore many important factors that together can contribute to the complete solution of the problem. As a result, we may get completely wrong or incomplete solutions [1]. For example, let's assume we want to design a chair, and one of the functional requirements is "It must be very comfortable." Being able to mathematically represent the phrase "*very comfortable*," greatly simplifies knowledge representation and manipulation of functional requirements. Fuzzy sets provide us with the ability to perform natural language computations and inexact reasoning. Fuzzy set is a class in which the transition from membership to non-membership is gradual rather than

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abrupt (Zadeh, 1972) [11]. For instance the class of comfortable chairs can be viewed as a fuzzy set. An executive chair is definitely a member of this fuzzy set with a high degree of membership (close to 1) and a classroom chair is more out of the set than it is in it. Because of the fuzzy characteristics of the functional requirements and design parameters, and the capability of mapping a fuzzy spatial pattern pair of FAM, this paradigm has been selected for the study.

FAM introduced by Kosko (1987), is a two layer feed forward, hetroassociative, fuzzy classifier that stores an arbitrary fuzzy spatial pattern pair (A_k, B_k) using fuzzy Hebbian learning, where the *kth* pattern pair are represented by the fuzzy sets [4], [7]:

$$A_k=\{a_1{}^k,\cdot,\cdot,\cdot,a_n{}^k\},\quad B_k=\{b_1{}^k,\cdot,\cdot,\cdot,b_p{}^k\}$$

$$W_{ij}=A^T\circ B=\min(M_A(a_i^K),M_B(b_j^k)) \qquad (2)$$

Where $M_A(a^k{}_i)$ is a degree of membership of *ith* member of the fuzzy set A (with the range of 0 to 1), Wij given in Equation 2 is a fuzzy connection strength from the *ith* to *jth* neurons. The recall equations for the first and second layer are given in Equations 3 and 4.

$$M_{A\circ W}(b_j)=\max_{i=1}^{n}[\min(a_i,W_{ij})] \qquad (3)$$

$$M_{B\circ W^T}(a_i)=\max_{j=1}^{n}[\min(b_j,W_{ij})] \qquad (4)$$

Conceptual design or generation of ideas is the highest level of creativity in the design process without any known algorithm. Some interesting connectionist works in design such as application of back propagation in conceptual design is done by Kumara and his colleagues (Kumara et al., 1990)[6], and possible applications of neural networks in feature based design is suggested by Dagli (1989) [2]. In this paper the feasibility of applying fuzzy associative memory and fuzzy knowledge representation for mapping functional requirements to physical structure is examined.

2. The Design Problem

Given sets of fuzzy functional requirements (FRs) and design constraints (Cs) generate the design solution(s) that can satisfy the input requirements. For instance, input requirement for designing a chair may stated as: *Design a very comfortable chair that can be used more or less in public.*

FR_1 = The chair must be *very comfortable.*

C_1 = *Use more or less in public.*

Having defined FRs and Cs, how do we generate design solution(s), namely a very comfortable chair that can be used more or less in the public. Design constraints have been differentiated from functional requirements since they are basically concerned with the boundary of the design such as size, weight and cost (the input constraints), or capacity, geometric shape and usage (the system constraints) [8]. In this paper the utilization of Fuzzy Associative Memory (FAM) in conceptual design is illustrated by applying it to the idea generation phase of chair design.

3. Fuzzy Knowledge Representations

Users and designers of systems usually communicate through a natural and somehow ambiguous language that cannot be modeled by conventional two-valued logic. Fuzzy sets can exploit the complexity and ambiguity that may result from communication gaps between users and designers, and turn them into manageable problem domains without ignoring the important factors involved. Fuzzy sets give us the building blocks for dealing with imprecise and overwhelming complex representation problem of input requirements.

To experiment with the concept, six generic functional requirements and 11 design constraints have been generated for designing various classes of chairs. Functional requirements are defined as: *Ability to adjust the chair* (FR1), *ability to move the chair* (FR2), *ability to fold the chair* (FR3), *stability* (FR4), *ability to stack the chair* (FR5), and *comfortability* (FR6). Design constraints are defined as: *Cost* (C1), *size* (C2), *weight* (C3), *use for dining* (C4), *use for office* (C5) *use for relaxations* (C6), use for home (C7), use for classroom (C8), use for public (C9), use for typing (C10), aesthetic look (C11). The crisp universal sets FRs of the functional requirements and Cs of design constraints are defined as follows:

$$FRs=\{FR1,FR2,FR3,FR4,FR5,FR6\}$$
$$Cs=\{C1,C2,C3,C4,C5,C6,C7,C8,C9,C11\}$$

A database of 11 different design solutions has been created, see Figure 1. Each design solution (chair) satisfies a certain set of functional requirements and design constraints. For instance an executive chair may be defined as follow:

$$fr(CHAIR2)=\{1.0/FR1,1.0/FR2,1.0/FR6\}$$
$$cs(CHAIR2)=\{1.0/C5,0.7/C6,0.3/C7,1.0/C11\}$$

The above fuzzy sets may be interpreted in English as follow: *An executive chair is a chair that is very comfortable with a high degree of adjustability and moveability, furthermore it is use more in the office than home, it also can be used for relaxation; finally the appearance is very important.*

The fuzzy sets labeled as CHAIR*n*, n=1 to 11, are the power sets containing all possible fuzzy subset of FRs and Cs.

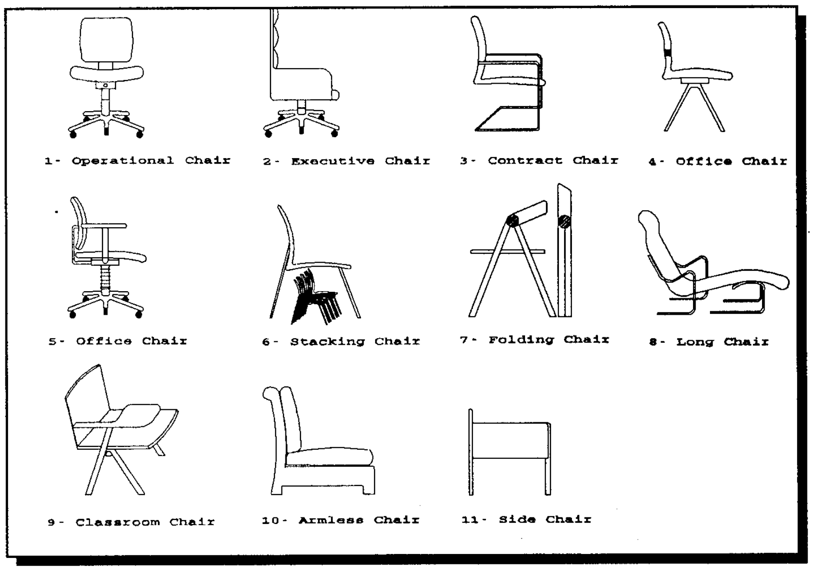

Figure 1. Design solutions.

$$\mu_{fr}:\tilde{\wp}(FR)\to[0,1]$$
$$\mu_{cs}:\tilde{\wp}(Cs)\to[0,1]$$
$$fr=\{\mu(x)/x|x\in FRs\}$$
$$cs=\{\mu(y)/y|y\in Cs\}$$

At the present time the sets FRs and Cs are of level 1 fuzzy sets with nesting of depth one. In the future extension FRs and Cs will be modified to level 2. This extension can be achieved by defining the linguistic variables such as adjustability (FR1), movability (FR2), foldability (FR3), stability (FR4), stackbility (FR5) and comfortability (FR6) as fuzzy sets, with similar extension for constraints.

4. Triggering and Conflict-Resolution Strategy

The primary disadvantage of FAM is in one-pair-storage capacity. Therefore, for each pattern pair, we must create a separate network. The main problem in implementing the multi-FAM model is the selection of a network based on an incoming pattern. For this problem we have the following:

Theorem 1: Given a set of n pattern pairs (A_k, B_k) and n FAMs, $A^T{}_k \circ B$ and a pattern pair (P, Q). The FAM that can map pattern P to Q and Q to P is the network that has stored the pattern pair (P, Q), or their subsets.

Proof: Suppose we have a pattern pair (A_m, B_m) and m is in [1, n], the following relations exist (Kosko, 1987a) [4,5]:

$$W_m = A_m^T \circ B_m \qquad (5)$$
$$B_m = A_m \circ W_m \qquad (6)$$
$$A_m = B_m \circ W_m^T \qquad (7)$$

Assume, There exist a pattern pair (P,Q) such that:

$$Q = P \circ W_m \qquad (8)$$
$$P = Q \circ W_m^T \qquad (9)$$
$$\therefore$$
$$P^T \circ Q = A_m^T \circ B_m \qquad (10)$$
$$P \circ Q^T = A_m \circ B_m^T \qquad (11)$$
$$\therefore$$
$$P \subset A_m \text{ and } Q \subset B_m.$$

An algorithm has been formulated to associate an incoming vector to the most applicable network. The proposed algorithm consists of two components, these are triggering, and conflict-resolution procedures. During triggering the incoming vector is feed forwarded and backward through all the networks and triggers each network to generate a vector. Conflict-resolution procedure resolves the conflict by selecting the network that has stored the closest vector to the incoming vector.

4.1 Trigger Procedure

Let's assume we have n networks, one for each pattern pair as follow:

$$W_1 = A_1^T \circ B_1,\ W_2 = A_2^T \circ B_2,\ W_3 = A_3^T \circ B_3,\ \cdots,\ W_n = A_n^T \circ B_n$$

Let's further assume R is a new incoming pattern. First, the vector R is fed through the first layer of each network. Each FAM generates pattern P_i, for i=1 to n.

$$P_1 = A_1 \circ W_1,\ P_2 = A_2 \circ W_2,\ P_3 = A_3 \circ W_3,\ \cdots,\ P_n = A_n \circ W_n$$

Next, pattern P_i is fed back through the second layer (output layer) of each network. Each FAM generates pattern Q_i. See Figure 2.

$$Q_1 = B_1 \circ W_1^T,\ Q_2 = B_2 \circ W_2^T,\ Q_3 = B_3 \circ W_3^T,\ \cdots,\ Q_n = B_n \circ W_n^T$$

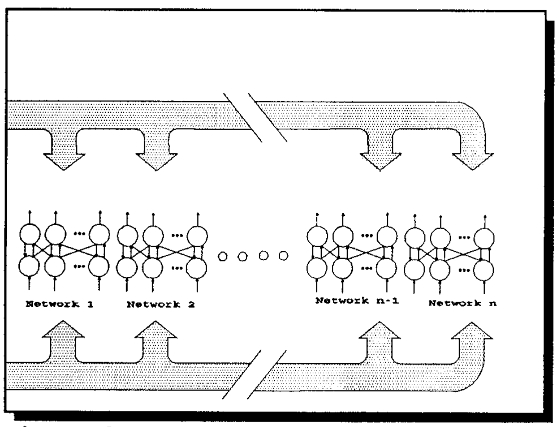

Figure 2.

4.2 Conflict-Resolution procedure

The conflict-resolution module compares pattern Q_i with the incoming pattern R. Equation 14 is used for measuring the closeness of patterns R and Q_i:

$$d(R, Q_i) = \sqrt{\sum_{j=1}^{n} (R_j - Q_{ij})^2}$$
$$S(R, Q_i) = \sum_{j=1}^{n} Q_{ij} R_J - |d(R, Q_i)| \qquad (14)$$

The network with the maximum value of S is the winner and it will be selected to do the mapping.

5. Network Topology and Data Set

The input as we discussed earlier, consists of two fuzzy sets, namely FRs and Cs. For the purpose of simplicity, these two sets have been represented as a list. Further, the symbolic representation has been replaced by the positional importance of the degrees of memberships in the list. The input layer is designed to have 17 neurons. One neuron for every functional requirement and design constraint. For example, the functional requirements and design constraints for executive chair (chair 2) are represented as follow:

A_2 = (1.0 1.0 0 0 0 1.0 0 0 0 1.0 0.7 0.3 0 0 0 0 1.0)

The first value corresponds to FR1 (*Ability to Adjust the Chair*), second to FR2 (*Ability to Move the Chair*) and so on. Each degree of membership is assigned to a separate neuron.

The output (second) layer of FAM is designed to have 11 neurons, one for every class of chair. For instance Chair 2 is represented as follow:

B_2 = (0 1.0 0 0 0 0 0 0 0 0 0)

6. Hybrid System Architecture and Implementation

The AutoCAD, a commercially available Computer Aided Design package has been selected as the basis for the user interface of the system. However, the concepts may be readily adapted for and rendered compatible with other CAD systems.

The proposed hybrid system is divided into two separate sections, front end and back end, see Figure 3. The front end provides the user interface, and the back end consists of fuzzy associative memory. The front end itself is divided into three sections, pre-processor, post-processor and AutoCAD. The pre-processor communicates with the designer and assists them in setting up the functional requirements and design constraints. The post-processor on the other hand converts the recall vector of the FAM to graphical representation and displays it. The back end does the actual mapping of input requirements to the design solutions. Back end is implemented in C++ and the pre and post-processors has been written in LISP.

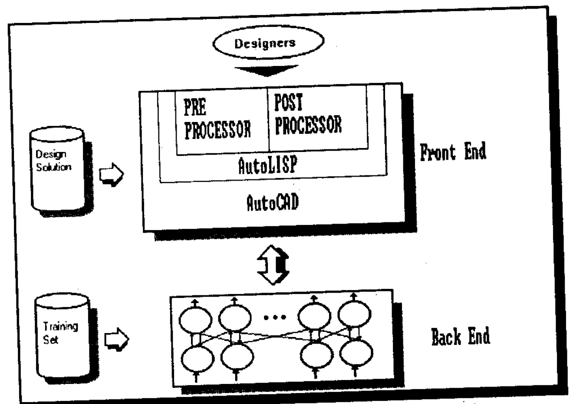

Figure 3. Hybrid system architecture.

7.0 Performance and Experimental Results

The system was trained on 11 pattern pairs (A_i, B_i), one pattern pair for each class of chair. To test the system, 16 design scenarios with known solutions have been created. The system was capable of successfully generating 14 correct solutions, see Table 1. For instance, the system was capable of correctly suggesting an executive chair despite the fact that the new input requirements were quite different from what it was trained on (see section 3 for the definition of an executive chair). In scenario number 10, it couldn't generate any solution. In scenario number 14, the system was requested to design a *somehow comfortable* classroom chair and it designed an armless chair which is very comfortable but not too practical for the classroom setting. Overall the system's error rate was less than 10%.

8.0 Concluding Remarks

In this paper the applications of Fuzzy Associative Memory in conceptual design by mapping fuzzy functional requirements to physical design has been examined. Trigger and conflict-resolution strategy has been proposed to solve the vectors association problem in multi-FAM environment. An extremely high rate of accuracy in retrieving fuzzy information, together with the simplicity of its practical implementation, makes this paradigm computationally attractive in the idea generation phase of the design process. This could establish the basic foundation of a true intelligent design machine, a tool that aids designers in all phases of the design process.

Table 1. Experimental Results.

No	Input Requirements (FRs and Cs)	Expected Design Solution(s)	Actual Design Solution(s)
1	{.8/FR2},{.5/C10}	Chair 1,5	Chair 1,5
2	{1/FR1},{1/C6,1/C11}	Chair 2	Chair 2
3	{1/FR6}, {1/C11}	Chair 2,10	Chair 10
4	{.8/FR4}, {1/C1, 1/C5}	Chair 3,4	Chair 3
5	{1/FR1,1/FR2},{.5/C10}	Chair 1,5	Chair 5
6	{1/FR1,.5/FR4},{.6/C1, 1/C5}	Chair 4	Chair 4
7	{1/FR5}, {.8/C1}	Chair 6	Chair 6
8	{1/FR5}, {.8/C4}	Chair 6	Chair 6
9	{.3/FR5}, {1/C4}	Chair 6, 11	Chair 11
10	{.3/FR5}, {.5/C4}	Chair 6, 11	None
11	{.8/FR4},{1/C6, .8/C7}	Chair 2,8,10	Chair 8
12	{1/FR6}, {1/C6, 1/C7}	Chair 8, 10	Chair 8
13	{.6/FR4}, {1/C8}	Chair 9	Chair 9
14	{.5/FR6}, {1/C8}	Chair 9	Chair 10 **
15	{1/FR6}, {1/C11}	Chair 2,8,10	Chair 10
16	{.8/FR6}, {1/C4}	Chair 11	Chair 11

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