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Intelligent Controller Based on Neural Network
Réseau neuronal en tant que système de contrôle intelligent
Neuronales Netzwerk als intelligentes Prüfsystem

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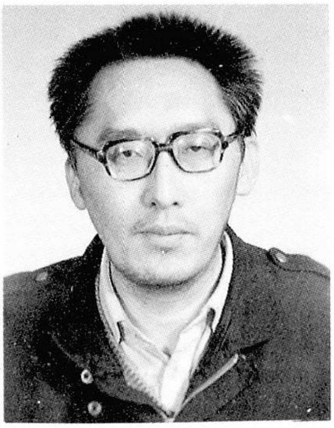

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SUMMARY
In the present paper, a new version of the knowledge-based system for structural preliminary design, which is based on neural networks, is introduced. Some intelligent control problems, such as the decisive influence of domain knowledge and the necessities of using controller are discussed. The measurability and controlability of the neural network controller are proved, and an intelligent controller based on Back-Propagation algorithm is developed. Finally, an application example is presented.

RÉSUMÉ
L'article présente une nouvelle version d'un système expert pour le prédimensionnement des structures, basé sur les réseaux neuronaux. Il décrit les problèmes relatifs à la surveillance intelligente, comme l'influence déterminante de la connaissance de base et la nécessité d'avoir recours à une fonction de contrôle. Un système de contrôle intelligent, dont la mesurabilité et la manoeuvrabilité ont été prouvées, a été développé en se basant sur l'algorithme de rétropropagation. Pour terminer, son utilisation est illustrée à l'aide d'un exemple.

ZUSAMMENFASSUNG
Der Beitrag präsentiert eine neue Version eines Expertensystems für die Vorbemessung von Tragwerken, basierend auf neuronalen Netzwerken. Dabei werden Probleme der intelligenten Ueberwachung, wie der entscheidende Einfluss der Wissensbasis und die Notwendigkeit einer Controller-Funktion erörtert. Ein intelligenter Controller mit nachgewiesener Mess- und Steuerbarkeit wurde auf der Basis des Back-Propagation-Algorithmus entwickelt. Die Anwendung wird an einem Beispiel gezeigt.

1. INTRODUCTION

The structural design is divided into three stages: the conceptual design, the preliminary design, and the construction design. Computer has been used widely in the construction design. For the time being, however, the application of computer in the preliminary design is still in its infancy. Obviously, the reason is that the construction design can be more easily performed by computer for its simplicity and systemic nature. In the preliminary design, however, both thinking in images and thinking in logic can not be avoided. One or more structural configurations that may provide the intended structural function must be generated. It is often to provide feedback on structural configurations or originally assumed key parameters to satisfy the architectural decisions. In fact, this stage is considered as the most creative phase of structural design. Obviously, it is hard computerised.

Artificial neural networks, as a new knowledge representation paradigm, is receiving a lot of attention and represents advancements. Neural networks are ideally suited for solving certain types of engineering problems that require a mapping from a large distributed set of input features to a large distributed set of output features, such as pattern association, etc. Thus, neural networks may be treated as a new representation mode of knowledge, especially related to thinking in terms of images. The first expert system for the preliminary design of high-rise buildings (HIDE-1), which is based on neural networks, was developed at Tsinghua University in 1989[1]. A new version (HIDE-2), which is based on a combination of neural networks with a rule base , was developed in 1990[2]. In 1991, a prototype for the preliminary design of space grid structures was developed[3]. In this system, each neural network is treated as a block which can be used not only as various knowledge representation modules but also as a simulation module, instead of the finite element calculation and an optimization module. However, it should be mentioned that SPRED-1 essentially relies upon a related data bank, which includes a number of previously designed similar projects. The data bank is used for learning of neural networks, it is so-called example-based reasoning.

In the present paper, a new version SPRED-2 is introduced, which can be used to consider special grid structures without enough previous examples or with very strong constraints. In the latter case, an intelligent controller based on neural networks is used. The emphasis of the present paper is put on how to use the controller to control the system to satisfy the designer's special requirements which is so-called constraints. Then, the controllability and the measurability of the intelligent controller are proved. Finally, a typical example for preliminary design of a spatial grid deck is given.

2. RETHINKING ABOUT DOMAIN KNOWLEDGE AND THE DESIGN PROCESS

In preliminary design, the thinking mode of design is a combination of both image thinking and logic thinking, which may have several scheme choices for a same project and usually the thinking path is not unique either. For this reason, it is rather difficult to formulate a mature model or algorithm for the thinking mode. The preliminary design, however, is a key stage during the whole design process, the choice of both structural schemes and some important parameters gives an essential effect on the structural design quality. Although the development of artificial intelligence brings us a promising light in the recent years, there are a few systems that can be used in practical engineering design. The reasons may be summarized as follows.(1) Many investigators, who are engaged in the research of knowledge-based systems, are experts only in artificial intelligent technique. Some of them want to accomplish a knowledge-based system only by the conversation with domain experts for several times. In fact, some subjects are concerned with deep knowledge, and most of domain knowledge can not be formalized by a artificial intelligent expert who has only a little talk with domain experts. The reasoning mode of an knowledge-based system depends, to a great extent, on domain knowledge. So domain experience plays an important role in formalization of a knowledge-based system. (2) During development of knowledge-based systems people often note the symbol process systems that is based on the logic thinking, but rarely pay more attention to the association mode, which is based on the image thinking. Therefore, the deeper reasoning ability is a conspicuous lack in the system, i.e., many systems are very sensitive to the object change and the knowledge acquisition becomes a "bottle neck".In the preliminary design process, the thinking mode of domain experts may have following characters. (1) The objective functions are related with one another, with structural schemes, design parameters and so on. The relations usually form a very strong network. In many cases, it can not be substituted by a hierarchical relation. (2) During the whole process, the objective functions and constraint conditions may be changed. (3) Designers hopes to obtain a most satisfactory solution among all the feasible solutions, but for different designers, the final decisions are very different. It seems very important to consider the three mentioned characters in the new system.

In the present paper, only spatial grid structures are considered, which can be shown in Fig. 1.

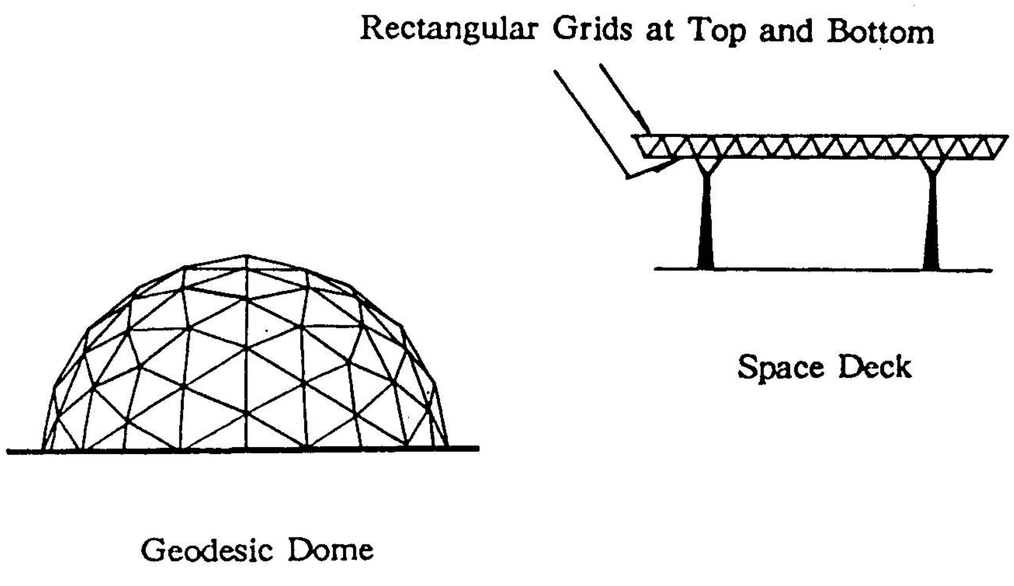

Fig.1 Typical spatial grid structures

3. THE PRESENT SYSTEM SPRED-2

The present system, SPRED-2, consists of three subsystems, each of them is designed for three following cases, respectively.

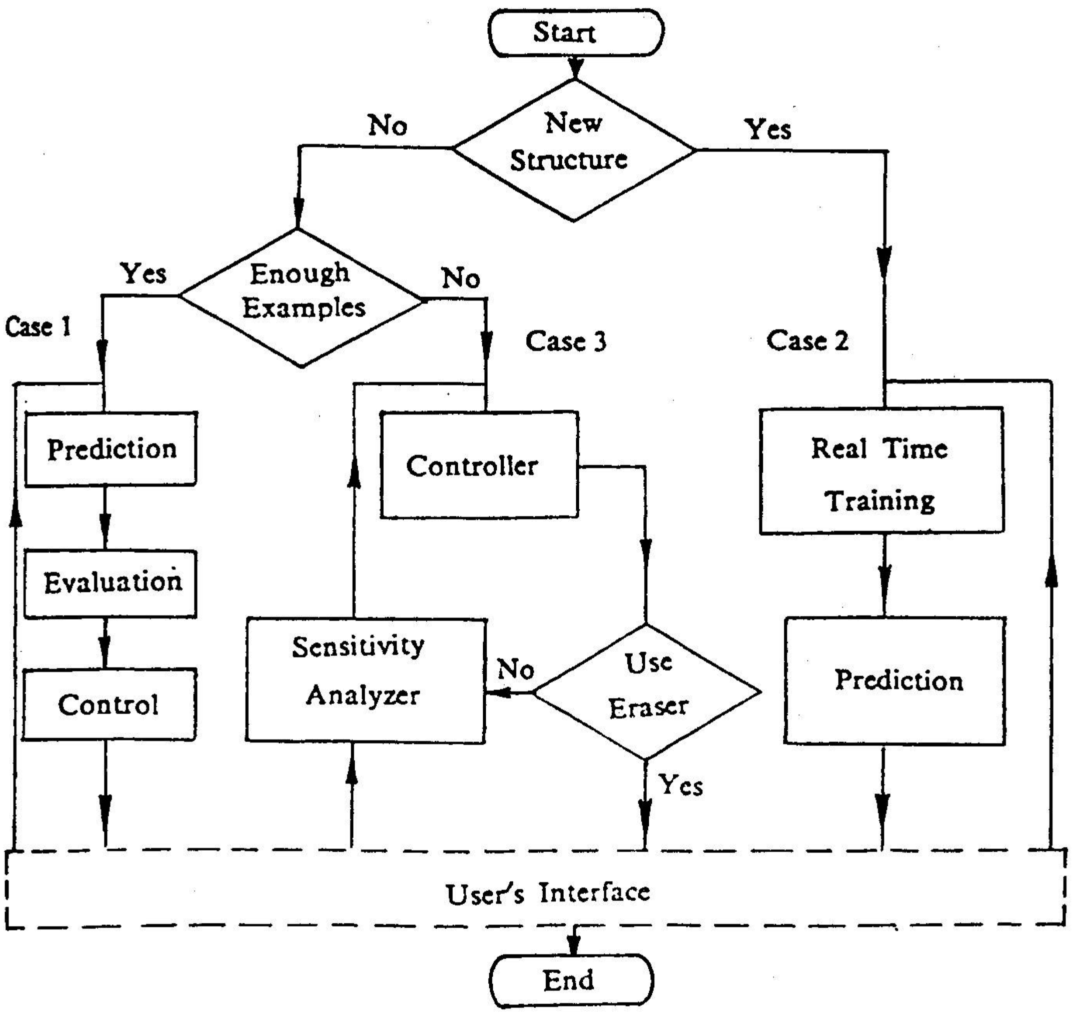

Fig.2 System architecture of SPRED-2

(1) **Case 1: To design common spatial grid structures with enough previous designed examples.** Since there are many samples used for reference, the structural configuration can be easily determined. The outputs obtained by the present subsystem usually have a little error to compare with the results from the finite element method (FEM). For this kind of structures, using both the rules given by knowledge base and the structural behaviour parameters from neural networks, the obtained optimal scheme can save 20%-30% total amount of steel. The original system, SPRED-1, becomes a subsystem of SPRED-2 and it is designed just for Case 1 only (Fig. 2). In this subsystem, many neural network moduli are used to simulate, evaluate and control the design process. In the prediction stage, a set of feasible schemes are created by a knowledge base and a data bank. Afterwards, each feasible scheme is evaluated by the evaluation part. Finally, the qualified feasible schemes should be optimized in the control part. If necessary, the optimal scheme can be checked or corrected by information fedback from the user's interface.

(2) **Case 2: To design special spatial grid structures without enough previous designed examples.** Since designers have no enough knowledge on this kind of structural behaviour, designers prefer to have a conservative scheme, and the amount of steel often increases. In the present subsystem, however, the real time training is used (Fig. 2). During this training process, first, the FEM is used to calculate a number of assumed structural samples similar to the new designed project. The assumed structural parameters here are selected by orthogonal tables. After calculation these assumed samples and their behaviours are learnt by a neural network modulus. All weight values in the modulus are also stored into a dynamic data base. Using dynamic data base with some rules from a knowledge base, the parameters for the new project, such as structural dimension, design load etc., can be given by a prediction modulus. Although these predicted structural parameters are approximate results compared with those determined by FEM, they can cut down 30-100% of the amount of steel obtained by designer's experience only. Usually the predicted accuracies are very satisfactory for the preliminary design. In addition, since the Davidom-Fletcher-Powell Method (DFP) is used to accelerate the convergency process[3], the inference time, even for B-P algorithm, is very limited. Therefore, the real time training for a new design project becomes possible.

(3) **Case 3: To design common spatial grid structures with some strong constraints or requirements.** In this case, the structure to be designed has almost common configuration, but some of its design parameters are constrained. For example, due to the space limitation, the grid depth is limited. Probably, due to the aesthetics requirement, the structural grid size or the maximum diameter of joints is limited. In these cases, therefore, structural engineers have to selects some parameters which are different from the most satisfactory points. It is very common that, in practice, structural engineers have to select some parameters which are not so satisfactory but very realistic within a feasible domain. On the other side, since the uncertainty of the aesthetics viewpoint, the constraint softening is also possible. In fact, during this design process, the revised information is often fedback to the original input nodes of the system to obtain a better scheme. It is so-called "the recursive process"[4]. The present subsystem Case 3 consists of three parts, i.e., a controller, a scheme eraser, and a sensitively analyser (Fig. 2), which can be explained as follows.

First of all, a neural networks with three layer perception is set in the intelligent controller, which has five input nodes (such as the structural plan dimension, the structural depth,grid lines, the number of the different member types, support conditions, and applied loads), and five output nodes (such as the total amount of steel, maximum internal forces, the maximum deflection, maximum reaction, and the maximum size of the joint). The link weights of the three-layer perception are from the prediction data bank of subsystem Case 1. When the original scheme with some strong constraints is given, a control algorithm can be used to give a most satisfactory feasible scheme. The basic idea is to adjust the values at hidden nodes of the three-layer perception, which will be introduced later. Afterwards, the scheme eraser works to check the obtained scheme by a knowledge base. Some unreasonable data may be deleted. In this case, the sensitivity analyser is driven to help designers or users to modify the input or output data. Then a new recursive process starts.

4. THE CONTROL ALGORITHM

First, an expected solution is defined as

$$\Phi = \{Z_1^*, Z_2^*, \cdots, X_1^*, X_2^*, \cdots\}^T \tag{1}$$

where $Z_1^*, Z_2^*, \cdots$ are expected output values from users, and $X_1^*, X_2^*, \cdots$ are expected input values. Then, an energy function can be assumed as

$$E = U + V \tag{2}$$

in which

$$U = \frac{1}{2}\left[(Z_1^* - Z_1)^2 + (Z_2^* - Z_2)^2 + \cdots\right] \tag{3}$$

where $Z_1, Z_2 \cdots$ are output values from the three-layer perceptron, and

$$V = \frac{1}{2}\left[(X_1^* - X_1)^2 + (X_2^* - X_2)^2 + \cdots\right] \tag{4}$$

where $X_1, X_2, \cdots$ are input values from the same perceptron. Now, the objective is to find the values $\{Y\}$ at hidden nodes of the perceptron, which can be treated as a conditional function, to make the energy function E minimum. It means that the obtained parameters $\{X\}$ and $\{Z\}$ represent the most satisfactory scheme. Before to perform the control algorithm, the controllability and the measurability should be proved first. Their definitions can be given as follows.

Controllability: For any given arbitrary value of $\{Y\}$, the initial conditional function $\{Y_0\}$ can change to $\{Y\}$ by finite modifications of $\{X\}$.

Measurability: For obtained output values $\{Z\}$, the conditional function $\{Y\}$ can be certainly determined.

Since the B-P algorithm is used in the present controller, each term of $\{Z\}$ and $\{Y\}$ can be given by following equations respectively.

$$Z_n = [1 + \exp(-\Sigma W_{nm} Y_m)]^{-1} \tag{5}$$

$$Y_m = [1 + \exp(-\Sigma W_{ml} X_l)]^{-1} \tag{6}$$

where l,m,n are subscripts of node values $\{X\}$,$\{Y\}$, and $\{Z\}$, respectively. W.. are connect weights. From Eq.(6), we have

$$\bar{Y}_m = \ln \frac{Y_m}{1 - Y_m} = \Sigma W_{ml} X_l \tag{7}$$

Symbolically, it is

$$[W]\{X\} = \{\bar{Y}\} \tag{8}$$

where $[W]$ is the weight coefficient matrix, $\{\bar{Y}\}$ is another expression of the conditional function $\{Y\}$.

If the rank of $[W]$ is the same as the number of hidden nodes m, then Eq.(8) must have unique solution, which means that the system is controllable. If the rank of $[W]$ is less than m, then no solution exists. Since in the present three-layer perceptron the number of hidden nodes usually are less than that of input nodes, this case hardly happens. If the rank of $[W]$ is larger than m, then multi-solution exists for Eq.(8). In this case, some input values can be assumed as constants to make the system controllable.

Similarly, from Eq.(5), we have

$$\bar{Z}_n = \ln \frac{Z_n}{1 - Z_n} = \Sigma W_{nm} Y_m \tag{9}$$

Symbolically, it is

$$[\bar{W}]\{Y\} = \{\bar{Z}\} \tag{10}$$

where $\{\bar{Z}\}$ is another expression of $\{Z\}$. If the rank of $[\bar{W}]$ is the same as the number of output nodes n,then Eq.(10) must have unique solution, which means that the system is measurable. If the rank of $[\bar{W}]$ is less or larger then n, there is no solution or multi-solution, which should be avoided.

In conclusion, if m=l and m=n, then the controllability and the measurability can be certainly guaranteed.

Now the control problem is to find a conditional function $\{Y\}$ or $\{\bar{Y}\}$ to minimize the energy function E. Here, the gradient method can be used.

From Eq.(2), for each m

$$\frac{\partial E}{\partial Y_m} = \frac{\partial U}{\partial Y_m} + \frac{\partial V}{\partial Y_m} \tag{11}$$

where

$$\frac{\partial U}{\partial Y_m} = \frac{\partial U}{\partial Z_1}\frac{\partial Z_1}{\partial Y_m} + \frac{\partial U}{\partial Z_2}\frac{\partial Z_2}{\partial Y_m} + \cdots \tag{12}$$

Let

$$\frac{\partial U}{\partial Z_1} = Z_1^* - Z_1 \tag{13}$$

$$\frac{\partial U}{\partial U_2} = Z_2^* - Z_2 \tag{14}$$

and so on, thus

$$\frac{\partial U}{\partial Y_m} = \sum_n (Z_n^* - Z_n) \frac{(-1)\exp(-\Sigma W_{nm} Y_m) W_{nm}}{[1 + \exp(-\Sigma W_{nm} Y_m)]^2} \tag{15}$$

Similarly,

$$\frac{\partial V}{\partial Y_m} = \frac{\partial V}{\partial X_1}\frac{\partial X_1}{\partial Y_m} + \frac{\partial V}{\partial X_2}\frac{\partial X_2}{\partial Y_m} + \cdots \tag{16}$$

Let

$$\frac{\partial V}{\partial X_1} = X_1^* - X_1 \tag{17}$$

$$\frac{\partial V}{\partial X_2} = X_2^* - X_2 \tag{18}$$

and so on, thus

$$\frac{\partial V}{\partial Y_m} = \sum_l (Z_l^* - Z_l) \frac{(-1)[1 + \exp(-\Sigma_{ml} X_l)]^2}{\exp(-\Sigma W_{ml} X_l) W_{ml}} \tag{19}$$

Substituting Eq.(15) and Eq.(19) into Eq.(11) the $\partial E/\partial Y_m$ for each m can be obtained. Thus the (k+1)th modification of $\{Y\}$ can be expressed as

$$\{Y\}_{k+1} = \{Y\}_k - \eta \left\{ \frac{\partial E}{\partial Y} \right\} \tag{20}$$

where η is a constant.

Using the newest $\{X\}$, $\{Y\}$, and {Z) can be done, which can be sent to the scheme eraser and be checked by a knowledge base.

5. THE APPLICATION EXAMPLE

Recently, a new design project, Zhong Guan Cun Shopping Center, has just been completed. The preliminary design of the project was done by SPRED-2. It is a double-layered space deck with 18x70m plan dimensions. At beginning, architects gave an original suggestion with very strong requirements on the structural depth and the maximum diameter of joints. According to the existing designed projects from the data bank, it seems that some requirements may be unreasonable. Using the Case 3 of SPRED-2, the final results can be done and shown in Table 1. It is the best compromising scheme between the original requirements and the collected domain knowledge. It can be seen that if the constraint on the structural depth from architects can be released, other parameters will be improved significantly.

	Original Scheme from Architects	Final Scheme Given by SPRED-2
Total amount of steel (kN)	891.8	646.8
Structural depth (m)	1.0	1.4
Max. internal force (kN)	196.0	137.2
Max. displacement (mm)	210	78
Max. size of joints (mm)	300	250

Table 1 The Structural Schemes of Zhong Guan Cun Shopping Center

6. REMARKS

(1) In the present, some characteristics of knowledge based systems in design are discussed. In order to imitate the thinking procedure of human being, the combination of both logic thinking mode and image thinking mode is needed and the domain knowledge is very important.

(2) The preliminary design of spatial structure is divided into three cases. The third case, which is used very widely in the preliminary design of spatial grid structures, is explained in detail in present paper.

(3) An intelligent controller is developed for obtaining the design parameters , which most close to the requirements given by the architects. Its controllability and measurability are proved. By adjusting the values of hidden nodes, the controller can be used to control the design variables and the structural parameters to obtain a most satisfactory scheme.

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