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SACON: A KNOWLEDGE-BASED CONSULTANT FOR STRUCTURAL ANALYSIS

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ABSTRACT

This paper presents an application of artificial intelligence methods to the engineering domain of structural analysis. We have developed and partially implemented an "automated consultant" called SACON (Structural Analysis CONsultant), using the EMYCIN system as its framework. SACON advises non expert engineers in the use of a large, general-purpose structural analysis program. The structure of the knowledge base, including the major concepts used and inferences drawn by the consultant, is presented. We conclude by making some observations in light of this application about the EMYCIN system as a representational vehicle and the process of acquiring knowledge for rule-based systems.

Key words: knowledge-based systems, knowledge acquisition, knowledge representation, automated consultant, structural analysis, inference structure.

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1 Introduction

We describe an application of artificial intelligence methods to structural analysis, in particular, the development and (partial) implementation of an "automated consultant" to advise non-expert engineers in the use of a general-purpose structural analysis program. The analysis program numerically simulates the behavior of a physical structure subjected to various mechanical loading conditions. The automated consultant, called SACON (Structural Analysis CONsultant), was constructed using the EMYCIN system, the domain-independent version of the MYCIN program [Shortliffe74]. Originally developed to advise physicians in the diagnosis and treatment of infectious diseases, the domain-specific medical knowledge in MYCIN is represented as production rules, and is kept independant of the "inference engine" that uses the rules. By substituting structural engineering knowledge for the medical knowledge, the program was converted easily from the domain of infectious diseases to the domain of structural analysis.

1.1 Motivation

The purpose of a SACON consultation is to provide advice to a structural engineer regarding the use of a structural analysis program called MARC [MARC76]. The MARC program uses finite-element analysis techniques to simulate the mechanical behavior of objects. The engineer typically knows *what* he wants the MARC program to do--e.g., examine the behavior of a specific structure under expected loading conditions--but does not know *how* the simulation program should be set up to do it. The MARC program offers a large (and, to the novice, bewildering) choice of analysis methods, material properties, and geometries that may be used to model the structure of interest. From these options the user must learn to select an appropriate subset that will simulate the correct physical behavior, preserve the desired accuracy, and minimize the (typically large) computational cost. A year of experience with the program is the typical time required to learn how to use all of MARC's options proficiently. The goal of the automated consultant is to bridge the "What-to-How" gap, by recommending an analysis strategy. This advice can then be used to direct the MARC user in the choice of specific input data--e.g., numerical methods and material properties. Typical structures that can be analyzed by both SACON and MARC include aircraft wings, reactor pressure vessels, rocket motor casings, bridges, and buildings.

In this report we describe the general structure of the structural analysis knowledge base, including the major concepts used and the inferences drawn by the consultant. We conclude by making some observations, in light of the SACON knowledge base, about the EMYCIN system as a representational vehicle and about the process of acquiring knowledge for rule-based systems. Further details of this application can be found in [Bennett78].

2 The SACON Knowledge Base

The objective of a SACON consultation is to identify an analysis strategy for a particular structural analysis problem. The engineer can then implement this strategy, using the MARC program, to simulate the behavior of his structure. This section introduces the mathematical and physical concepts used by the consultant when characterizing the structure and recommending an analysis strategy.

2.1 Consultation Parameters

An analysis strategy consists of an analysis class and a number of associated analysis recommendations. Analysis classes characterize the complexity of modelling the structure and the ability to analyze the material behaviors of the structure. Currently, 38 analysis classes are considered; among them, *Nonlinear geometry crack growth*, *Nonlinear geometry stress margin*, *Bifurcation*, *Material instability*, *Inelastic stiffness degradation*, *Linear analysis*, and *No analysis*. The analysis recommendations advise the engineer on specific features of the MARC program that should be activated when performing the actual structural analysis. The example consultation concludes with 9 such recommendations (see below).

To determine the appropriate analysis strategy, SACON infers the critical material stress and deflection behaviors of a structure under a number of loading conditions. Among the material stress behaviors inferred by SACON are *Yielding collapse*, *Cracking potential*, *Fatigue*, and *Material instabilities*; material deflection behaviors are *Excessive deflection*, *Flexibility changes*, *Incremental strain failure*, *Buckling*, and *load path bifurcation*.

Using SACON, the engineer decomposes the structure into one or more substructures and provides the system the data describing the materials, the general geometries, and the boundary conditions for each of these substructures. A substructure is a geometrically contiguous region of the structure composed of a single material such as high-strength aluminum or structural steel and having a specified set of kinematic boundary conditions. A structure may be subdivided by the structural engineer in a number of different ways; the decomposition is chosen which best reveals the worst-case material behaviors of the structure.

For each substructure, SACON estimates a numeric total loading from one or more loadings. Each loading applied to a substructure represents one of the typical mechanical forces on the substructure during its working life. These might, for example, include loadings experienced during various maneuvers such as braking, banking, etc., for planes or, for buildings, loadings caused by natural phenomena such as earthquakes or wind-storms. Each loading is in turn composed of a number of point or distributed load components.

2.2 Reasoning Steps

Given the descriptions of the component substructures and the descriptions of the loadings applied to each substructure, the consultant estimates stresses and deflections for each substructure using a number of simple mathematical models. The behaviors of the complete structure are found by determining the sum of the peak relative stress and deflection behaviors of all the substructures. Based on these peak responses (essentially the worst-case behaviors exhibited by the structure), its knowledge of available analysis types, and the tolerable analysis error, SACON recommends an analysis strategy. Figure 1 illustrates the basic inferences drawn by SACON during a consultation.

```
    Inferred Parameters     |     Context Level
  --------------------------+-----------------------
                            |
    Analysis Strategy       |     Structure
          ↑                 |
    Worst-case Stress and   |
      Deflection Behaviors  |     Structure
          ↑                 |
    Stress and Deflection   |
      Behaviors             |     Sub-structures
          ↑                 |                     Symbolic
  - - - - - - - - - - - - - + - - - - - - - - - - - - -
          ↑                 |                     Numeric
    Composite Stress and    |
      Deflection Estimates  |     Loadings
          ↑                 |
    Stress and Deflection   |
      Magnitudes            |     Load Components
                            |
```

Fig. 1 Inference structure during the consultation. The user specifies loading and substructure descriptions that SACON uses to infer material behaviors and, finally, an analysis strategy.

Knowledge about the structural analysis task is represented in the form of production rules. An example rule, which provides the transition from simple numeric estimates of stress magnitudes to symbolic characterizations of stress behaviors for a substructure, is illustrated below. For details on this representational scheme, see [Shortliffe74].

```
RULE050
-------
  If:  1) The material composing the sub-structure is
          one of: the metals, and
       2) The analysis error (in percent) that is tolerable is
          between 5 and 30, and
       3) The non-dimensional stress of the sub-structure is
          greater than .9, and
       4) The number of cycles the loading is to be applied is
          between 1000 and 10000
  Then:  It is definite (1.0) that fatigue is one of the
         stress behavior phenomena in the sub-structure

PREMISE:    ($AND (SAME CNTXT MATERIAL (LISTOF METALS))
                  (BETWEEN* CNTXT ERROR 5 30)
                  (GREATERP* CNTXT ND-STRESS .9)
                  (BETWEEN* CNTXT CYCLES 1000 10000))
ACTION:     (CONCLUDE CNTXT SS-STRESS FATIGUE TALLY 1.0)
```

The existing knowledge base is able to select from among 36 nonlinear analysis strategies. If nonlinear analysis is not indicated by the response estimates, the consultation recommends linear analysis. In addition, if relative stress and displacement estimates are low (less than 5% of critical values), the consultation indicates that no analysis is required. The knowledge base consists of 170 rules and about 140 consultation parameters. A typical consultation (2 substructures, 3 loadings, 3 load components) requires about 25 minutes at an interactive terminal.

To bring the SACON program to its present level of performance, we estimate that two man-months of the experts' time were required to explicate the consultation task and formulate the knowledge base, and about the same amount of time to implement and test the rules.[1] For the first 170 rules in the knowledge base, the average cost of formulating and implementing a rule was about 4 hours. The marginal cost for a new rule is about 2 hours.

[1] This estimate does not include the necessary time devoted to meetings, problem formulation, demonstrations and report writing.

2.3 An abbreviated example

The following transcript illustrates SACONs interactions with an engineer and SACON's recommendation of an analysis strategy.

```
[consultation of 13-Jul-78 1:55PM]

   --------STRUCTURE-28--------
   1) What is the name of STRUCTURE-28?
   ** BOEING 747 WING
   2) Assuming that your characterization of the boeing 747 wing in terms of
      its geometry, material characteristics, and boundary conditions are
      accurate, how much error (in percent) is tolerable for the analysis?
   ** 10
   3) Do you want to examine the responses of the boeing 747 wing , to
      evaluate its instability, or both?
   ** EXAMINE-RESPONSES
   .
   .
   .
   6) Have you decomposed the boeing 747 wing into a number of potential sub-
      structures which are relevant to this analysis?
   ** YES

      --------SUB-STRUCTURE-1--------
      7) What is the name of SUB-STRUCTURE-1?
      ** TOTAL WING
      8) What is the material composing most of the total wing (SUB-
         STRUCTURE-1)?
      ** HIGH-STRENGTH-ALUMINIUM
      9) Enter the average longest dimension of the total wing (SUB-
         STRUCTURE-1) in inches (or <number> CMS):
      ** 1420
      10) Enter the weight of the total wing (SUB-STRUCTURE-1)  in pounds (or
          <number> KGS):
      ** 46000
      11) Is the total wing (SUB-STRUCTURE-1) thin-walled or solid?
      ** THIN-WALLED
          .
          .   [More questions are asked of the user about this and
          .      and any other sub-structures involved in the consultation.]

   26) Do the supports of the boeing 747 wing involve Coulomb friction,
       nonlinear springs, and/or gapping?
   ** NO

The following analysis classes are relevant to the analysis of your structure:
       1) general-inelastic

(The following recommendations apply to this case:)

     Activate incremental stress - incremental strain analysis.
```

Model nonlinear stress-strain relation of the material.

Solution will be based on a mix of gradient and Newton methods.

Logic to scan peak stress at each step and evaluate fatigue integrity should be used.

Logic to scan stresses, smooth, and compare with allowable stresses (with appropriate safety factors) should be used.

Logic to scan deflections, calculate relative values, and compare with code limits, should be called upon.

Cumulative strain damage should be calculated.

Analysis should include two or more load cycles (if cyclic) with extrapolation for strain accumulation.

Shakedown extrapolation logic should be used.

3 EMYCIN as a Knowledge Representation Vehicle

A primary goal of this research was to determine if current "knowledge-engineering" techniques could be usefully applied in the development of a computer-based consultant in structural analysis. Specifically, our research was a test of the applicability of the rule-based formalism of the EMYCIN system. As such, we neither explored the use of other available consultation systems (e.g. PROSPECTOR, RITA) nor examined the pros and cons of using the different representation schemes that they provide.

At no time did we find the representation formalism of EMYCIN to be a hindrance to either the formulation of the knowledge by the expert or its eventual implementation in the SACON program. In fact, the simplicity of using and explaining both EMYCIN's rule-based formalism and its backward-chaining control structure actually facilitated the rapid development of the knowledge base during the early stages of the consultant's design. Moreover, the control structure, like the rule-based formalism, seemed to impose a salutary discipline on the expert as he formulated the knowledge base.

One major feature of EMYCIN that was not used in this task was the confidence factor mechanism [Shortliffe74]--i.e., the ability to draw inferences with uncertain knowledge. The present consultation strategy and the associated mathematical models were designed to estimate extreme loading conditions, from which SACON concludes the appropriate analysis class. Consequently, by using a "conservative" model, the rules, though inexact, are sufficiently accurate for predicting response bounds with certainty.

4 Validation of Domain-Independence

The development of SACON represents a major test of the domain-independence of the EMYCIN system. Previous applications using EMYCIN have been primarily medical with the consultations focusing on the diagnosis and prescription of therapy for a patient. Structural analysis, with its emphasis on structures and loadings, allowed us to detect the small number of places where this medical bias had unduly influenced the system design, notably text strings used for prompting and giving advice.

Our expert found that his knowledge was easily cast into the rule-based formalism and that the existing predicate functions and context-tree mechanism provided sufficient expressive power to capture the task of recommending an analysis strategy. The existing interactive facilities for performing explanation, question-answering, and consultation were found to be well developed and were used directly by our application. None of these features required any significant reprogramming[1] and, for the most part, worked without modification.

[1] The project required the development of three new predicate functions and a minor modification to the consultation facilities to handle certain user interactions in a more natural fashion. These extensions are now included in the EMYCIN system.

5 Observations about Knowledge Acquisition

Our experience explicating the structural analysis rule base provided an opportunity to make some observations about the process of knowledge acquisition for consultation systems. Although these observations were made with respect to the development of SACON, other knowledge-based consultation systems have noted similar processes and interactions.

Our principal observation is that the knowledge acquisition process is composed of three major phases. These phases are characterized strongly by the types of interaction that occur between expert and knowledge engineer and by the type of knowledge that is being explicated and transferred between the participants during these interactions. At present only a small fraction of these interactions can be held directly with the knowledge-based system itself [Davis77] [Davis76], and research continues to expand the knowledge acquisition expertise of these systems.

5.1 The Beginning Phase:

The beginning phase of the knowledge formalization process is characterized by the expert's ignorance of knowledge based systems and his unfamiliarity with the process of explicitly describing exactly what he knows and does. At the same time, the knowledge engineers are notably ignorant about the application domain and clumsily seek, by analogy, to characterize the possible consultation tasks that could be performed (i.e., "Well, in MYCIN we did this....").

During the initial weeks of effort, the domain expert learns what tools are available for representing his knowledge, and the knowledge engineer becomes familiar with the important concepts of the domain. During this period the two formulate a taxonomy of the potential consultation areas for the application domain and the types of advice that could be given. Typically, a small fragment of the complete spectrum of consultation tasks is selected to be developed during the following phases of the knowledge acquisition effort. For example, the MYCIN project began by limiting the domain of expertise to the diagnosis and prescription of therapy for bacteremia (blood infections); SACON is currently restricted to determining analysis strategies for structures exhibiting nonlinear, nonthermal, time-independent material behaviors.

5.2 The Middle Phase:

Having decided on the subdomain that is to be developed, the team next concentrates on identifying a large portion of the domain vocabulary (parameters, values, and contexts) and the reasoning steps (rules). These will be used to characterize the object of the consultation (be it patient or airplane wing) and to recommend any advice. After this conceptual groundwork is laid, work proceeds to detail the reasoning chains and develop the major rule sets in the system. Enough knowledge is explicated during this middle phase to advise a large number of common cases.

While developing the SACON system, we profited during this period by 'hand-simulating' any proposed rules and parameter additions. In particular, major advances in building the structural analysis knowledge base came when the knowledge engineer would "play EMYCIN" with the expert. During these sessions the knowledge engineer would prompt the expert for tasks that needed to be performed. By simulating the back-chaining manner of EMYCIN we asked, as was necessary, for rules to infer the parameter values, 'fired' these rules, and thus defined a large amount of the parameter, object, and rule space used during the present consultations. This process of simulating the EMYCIN system also helped the expert learn how the program worked in detail; he was then able to develop more rules and parameters on his own.

5.3 The End Phase:

Finally, when the knowledge base is substantially complete, the system designers concentrate on *debugging* the existing rule base. This process typically involves the addition of single rules to handle obscure cases and might involve the introduction of new parameters. However, the major structure of the knowledge base remains intact (at least for this subdomain), and interactions with the expert involve relatively small changes.

The development of the knowledge base seems to be facilitated if the knowledge engineering team elicits a well-specified consultation goal for the system as well as an inference structure such as that depicted in Figure 1. Without this conceptual structure to give direction to the knowledge explication process, a confused and unusable web of facts typically issues from the expert. We speculate that the value of these organizational structures is not restricted to the production system methodology. They seem to be employed whenever human experts attempt to formalize their knowledge using some representation formalism, be it production rules, predicate calculus, frames, etc. Indeed, when difficulties arise in building a usable knowledge base, we expect that the trouble is as likely to be because of a poor choice of inference structure than from the use of a particular representation scheme.

The inference structure is a form of *meta-knowledge*, i.e. knowledge about the structure and use of the domain expertise. Our experience shows that this meta-knowledge should be elicited and discussed early in the knowledge acquisition process, in order to insure that a sufficient knowledge base is acquired to complete a line of reasoning, and to reduce the time and cost of system development.

Currently, the inference structure is not an explicit part of the program (or of any other expert system of which we are aware), and hence is unavailable for the purposes of explanation, tutoring, or further acquisition of the knowledge base. Its critical role in building a successful knowledge engineering application, however, would suggest making such meta-knowledge an explicit part of the consultation system. Following [Davis76], future research on the interactive acquisition of knowledge from experts should benefit from the representation and use of such domain-specific meta-knowledge.

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