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UNITÉ DE RECHERCHE
INRIA-LORRAINE

Rapports de Recherche

1992

ème anniversaire

N° 1590

Programme 3
Intelligence artificielle, Systèmes cognitifs et Interaction homme-machine

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Janvier 1992

RR-1590

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AITRAS : UN SYSTEME EXPERT TEMPS REEL POUR LA COMPREHENSION DE SIGNAUX*

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Résumé :

Ce papier présente une architecture multi-agents que nous avons conçue pour l'interprétation de signaux. Cette architecture a été développée dans le cadre du projet européen ESPRIT AITRAS dont le but est de réaliser un nouvel outil de développement de systèmes d'interprétation en temps réel. Les points forts de cette architecture sont :

• la connexion entre le niveau de traitement du signal et de reconnaissance de formes, d'une part, et l'interprétation symbolique, d'autre part,

• une structure mixte combinant un modèle de tableau noir et une communication explicite entre modules par un mécanisme de passage de messages. Cette structure étend le modèle de société de spécialistes que nous avons proposé précédemment (Gong, 1989),

• l'intégration du raisonnement hypothétique.

Nous nous concentrons dans ce papier sur le premier prototype réalisé dans le cadre du projet. L'application concerne l'inspection des tubes d'un générateur dans une centrale nucléaire par une méthode non destructive fondée sur les courants de Foucault. Nous montrons en particulier l'apport des techniques de l'intelligence artificielle à de telles applications.

N° de programme INRIA : 3 (Intelligence artificielle, sciences cognitives et interaction homme-machine)

* Papier accepté au "World Congress on Expert Systems", Orlando, USA, Dec. 1991.

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This paper deals with a multi-agent architecture that we have developed for signal understanding. The architecture we propose has been developed in the framework of the AITRAS ESPRIT project of the EEC which aims at designing a new shell for the implementation of real time signal interpretation systems. The strong points of the architecture are :

• the connection between low level signal and pattern recognition modules on one hand and symbolic interpretation on the other,

• a mixed structure combining a blackboard model with explicit communication between modules by a message passing mechanism. In this respect, this new architecture extends the specialist society model that we developed earlier (Gong, 1989),

• the integration of hypothetical reasoning.

In this paper, we will mainly concentrate on the first demonstrator of the project. It concerns eddy current inspection for the non destructive examination of steam generator tubes in nuclear power plant. We will emphasize the enhancement that Artificial Intelligence technology provides in order to deal with such applications.

* The authors wish to thank J.M. André, M. Audrain, J.P. Benoit, C. Bouque, P. van Cleven, J.C. Coriton, A. de Feyter, J. Guerra, M. Katz, P.F. Kerdiles, R. Martinez-Oña, R. Occhipenti, J. Vasquez-Fernandez and M. Zavadsky for their valuable contribution as members of the project team.

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Abstract :

This paper deals with a multi-agent architecture for signal understanding. This architecture has been developed in the framework of the AITRAS ESPRIT project of the EEC which aims at designing a new shell for the implementation of real time signal interpretation systems. The strong points of the architecture are :

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KEYWORDS

Knowledge-based System, Signal Understanding, Hypothetical Reasoning, Multi-agent Architecture, Real time

INTRODUCTION

Problem definition

An important task in a nuclear plant consists of non destructive examination of steam generator tubes (Dobbeni, 1987). The steam generator ensures the heat transfer between the primary radioactive coolant loop and the secondary clean coolant loop isolating radioactive coolant from turbine. Safety requirements necessitate inspection at regular intervals of more than 100 km of tubes composing a steam generator (STG). The defects which have to be detected may be less than 1 mm in length which explains the difficulty of the analysis task.
Eddy current inspection is one of the techniques which are used to perform the examination. It consists in examining the output of moving coils passing inside the tube. The coils, connected to an appropriate impedance bridge and operating in either differential or absolute mode, generate a primary electromagnetic field and receive the secondary magnetic field induced by the eddy current flow circulating in the test piece. This environment is mainly composed of the tube wall and the surrounding conducting parts in proximity of the tube wall. The depth of penetration of the electromagnetic field is inversely proportional to the square root of the eddy current frequency. Therefore multiple frequencies are commonly used in order to obtain a more complete image of the possible degradation phenomena.
Numerous sources of signals can be encountered during the inspection. Most of them are known since they originate from known support structures or known changes in the tube dimension. The other signals not attribuable to design or manufacturing sources are of particular interest since they can be caused by a degradation phenomenon. These signal can be observed either in the proximity of known structural discontinuities or in a region free from known electromagnetic influences. When the degradation occurs close to a known signal, it modifies the expected shape and creates a complex signal. Other complex signals are produced when several degradations are close enough to be sensed simultaneously by the eddy current field.

Overview of the analysis task

The eddy current analysis of steam generator tubing can be divided into three main tasks :
1) signal detection consists of the selection of any eddy current signal that exceeds an amplitude threshold on either one or both channels of each detection frequency and/or mixings. Each two channel pair is the projection of the coil-tube impedance locus on the resistive and reactive axis. The number of abnormal signals that are detected will contain a certain number of "false-calls". For one STG, more than 1000 sheets resulting from the signal detection task must be examined by human experts in order to carry out the other two tasks.
2) signal identification is achieved by an human expert who tries to relate the signal to the tube and the environment characteristics that created its pattern. This task is context sensitive and implies knowledge of the signal features that differentiate a false-call from a signal related to a loss of material or any other degradation. For expected signals, the expert uses a priori information derived from his previous experience. In general, the analyst develops a heuristic measure of normality based on his experience and conditions unique to a particular steam generator or a subset of tubes.
3) defect characterization analyses the signal features in order to determine the defect parameters such as penetration depth, length or width.

Analysis by the expert

The results of step 1) described above are a set of sheets containing several signal representations :
• temporal signal for each frequency and each channel,
• Lissajous diagrams combining the two channels.
In order to analyze a sheet the human expert uses :
• a set of primitive symbols, or features, visually extracted from the signal both in Lissajous' representation and in temporal series representation (the signature level).

• the position of the tube in the steam generator and the location within the tube,
• the signal shape of known electromagnetic discontinuities,
• the history of the tube, including tube manufacturing and the result of pre-service inspection and previous field service inspection,
• a number of diagnosis rules using the above mentioned information,
• some analysis strategies such as the way of selecting an inspection frequency.

Starting from the features, the expert tries to identify shapes produced by some component of the steam generator (tube support plate, anti vibration bar, ...). Then he tries to identify a set of possible defect (corrosion, shock denting, ...) depending on the location of the coil in the tube. Then he looks at other frequencies to extract new features (phases, amplitudes,...) to negate or confirm the previous hypotheses. The expertise is twofold : visual expertise to extract features from diagrams and heuristic expertise by using knowledge derived from his previous experience.

The expert also uses historical data accumulated during the previous inspections of the tube in order to confirm his diagnosis and see if the defect is evolving. When a defect is found, the expert tries to find the origin of the defect and its depth in order to decide on repairing or plugging the tube.

Objective of the AITRAS project

We aim at using AI techniques for modeling and automating the reasoning process of experts in the task that we presented in the previous section. These tasks are highly critical for both safety and cost issues. Indeed the inspected power plant must be stopped during the examination. So the study of more than 1000 sheets must be performed as fast as possible. As this work is repetitive and monotonous, three teams of high level experts are involved in order to reject possible wrong diagnoses.

One objective of our project consists in reducing the number of sheets which have to be examined by a human expert so that only the difficult and interesting cases would be given such treatment. When needed he could also be involved in interaction with the computer to remove the ambiguities.

METHODOLOGY

Introduction

We are particularly interested in interpreting industrial signals with the following requirements :
• the process for understanding a signal requires large amounts of knowledge coming from different abstract levels,
• the interpretation process should follow continuous changes of the physical process and integrate them into the ongoing interpretation.

These needs involve significant problems to be solved by artificial intelligence technology :
• cooperation between various knowledge sources including different reasoning schemes,
• processing large amounts of concurrent hypotheses associated with their context and certainty.

In order to deal with these problems, we have designed a generic real-time signal interpretation system. Our system consists of :
• a multiple knowledge source framework, which provides an environment for multiple agents to build up interpretation solutions opportunistically and incrementally, and develop processing units independently from different abstraction levels. The multi-agent paradigm has already been employed with significant success for similar interpretation problems (Engelmore, 1988), (Maître, 1989), (Gong, 1989).
• a hypothetical reasoning system, which maintains a constraint set from different interpretation levels, generates explanations and deals with uncertainty in current interpretations.

Multi-agent architecture

Multi-domain knowledge

The construction and validation of an interpretation require verifying the coherence between the models defined by a priori knowledge about the signal and the observed signal. Understanding a physical process may involve a variety of concepts, relations and ways of exploiting them. Consequently, knowledge sources which define signal models by describing the relationships and implication of objects will cover several conceptual domains. Domains can be hierarchical, in which case they will be called levels. We will use indifferently domain and level.

A multi-level knowledge representation and control mechanism is needed in signal interpretation, because such a task presents special properties :

• **incremental solution construction** : A complex problem is divided into reasonable size sub-problems and solution-contributing agents work cooperatively for incremental solution construction.

• **data representation :** Different domains imply differences in nature of objects and relationships, since they are different in semantics. In each domain, existing physical models can be exploited for problem solving.

• **problem solving strategy :** To each nature of problem, there exists a specific reasoning mechanism and an adapted local control. A decentralized control structure will permit efficient knowledge organization, since organizing grouped agents is easier than organizing them individually.

• **domain dependency** : information producing-consuming relations exist between domains. Some domains may be able to verify hypotheses generated by others, or to generate hypotheses to be verified by others.

• **information exchange :** During the interpretation process, within one problem domain, knowledge sources may have intensive information exchange among them whereas between different domains only a loose coupling is required which allows the communication of identified structures.

Design of a multi-knowledge base system

In the design of a multi-knowledge base system, several parameters must be considered. Among these parameters, the characteristics of knowledge sources (KSs) must be cited : homogeneous or heterogeneous structure, protocol of communication (i.e. communication by sharing or transmitting information), type of control adopted in order to coordinate this communication as well as the status of the universe on which the KSs function (i.e. static or dynamic), etc.

Different architectures for organizing and controlling multiple knowledge sources have been proposed. As regards communication of information between KSs, two approaches exist.

One uses communication by information-sharing. This implies memorization of the current state of the problem in a structure common to all KSs. This structure then englobes initial data and different partial results given by KSs at each step of the problem-solving process. This guarantees a certain reliability of the system. This type of communication is implemented in the blackboard model. More precisely a blackboard-based architecture consists of a set of agents, known as knowledge sources or KSs, which communicate with each other through a shared global database, the blackboard, containing all necessary domain information called solution or hypothesis elements. A controller mediates the execution of enabled KSs. KSs have a precondition-action format. Preconditions describe situations in which the KS can contribute to the problem-solving process while the action parts specify the KS's behavior. Only those KSs whose preconditions are satisfied can actually perform their actions. The blackboard model corresponds to a high level description, and says nothing about how it can be computationally implemented.

A second communication approach uses the message passing mechanism, as defined in the object oriented formalism. Actors languages were the precursor of this kind of communication.

Blackboard and Actors paradigms afford advantages and disadvantages. In order to improve these models some studies have been engaged by mixing these approaches. The expert society paradigm is one of them. We have developed such a system at CRIN-INRIA in the so-called specialist society (Gong, 1989).

The blackboard structure provides a scheme for multiple knowledge source organization. In spite of its success in various applications, this model is felt unsatisfactory in the following aspects, due to its global, one-level control mechanism :

• explicitly implementing a given searching strategy.

• independently studying separate levels of knowledge sources ; in fact, it is difficult for a level to explicitly express its needs and send partial solutions to others. Consequently, implementing an explicit communication would require modifying the natural structuring of the problem, whereas recompiling an

explicit communication would require modifying the natural structuring of the problem, recompiling solution elements and redefining the control mechanism.
• including a local control for each abstract knowledge level.
The specialist society that we propose aims at overcoming these difficulties.

Specialist society

A specialist society consists of several separate associations, each modeling an abstract problem level related to a specific domain. The knowledge about a problem is partitioned into associations according to the levels of abstraction and then, within each association, implemented by a group of independent specialists. A specialist is a dynamic problem solving entity specialized in one aspect of the construction of a solution at one level. Specialists belonging to a particular association share a conference where they can read and write partial solutions and problem solving states. The communication between associations is ensured by a message passing mechanism.
The control of the interpretation activity is based on two modes of information exchange : communication between specialists via the modification of the domain conference (for specialists in one level) and communication between associations by message passing (a message contains partial interpretations). Therefore it combines memory sharing (blackboard paradigm) and message passing mechanisms (object-oriented framework). The control of the specialist society is opportunistic and operates in two steps : the global control realizing the message passing and actioning an association, and the local control within an association which dynamically determines the order of execution of the specialists in the level, allowing a particular control strategy in each association.
During a session, an association first receives partial solutions - the hypotheses - from another association of higher or lower abstract level. The specialists then discuss in the conference, creating, deleting and modifying partial solutions. These solutions, which are correct only locally in the association, are then sent as part of a message to another association which is competent in contributing further to the solution. By activating the associations at different levels the uncertainty of the signal is progressively removed.
The specialist society model meets the requirements of real-time signal interpretation in the following aspects :
• **real-time requirement** : The architecture takes into account more information on domain relations and allows removal of rating coefficients while retaining opportunism. In addition, distributed domains allow conferences to be implemented on separate machines.
• **variety of processing schemes** : Each level has its specific strategy. If specified by a global control mechanism, identifying the context of the level and describing the control of the level would require a large search space and therefore be difficult to carry out.
• **explicit bottom-up and top-down processing** : The complexity of the signal interpretation problem requires mixed reasoning.
• **module independence** : The associations working in a same society exchange messages without explicitly knowing each other's location or even existence. This property facilitates the independent development of individual modules.
• **flexibility and genericity :** each association is functionally independent ; the replacement or the adaptation to a new application is facilitated.

Assumption-based reasoning

Problem definition

Both the indeterminism of the signal analysis and the processing of incomplete information imply multiple interpretations. Therefore multiple hypotheses must be managed. In conventional blackboard systems all pieces of information present in the common data area are hypotheses. If this approach is general enough for problem solving, it however does not provide any help for assuring the logical and semantic consistency of the deductions that are made. For example, the arrival of complementary information can further invalidate certain assumptions and thus raise questions concerning some of the deductions. As a result we need recording data dependency in order to provide an automatic maintenance of the knowledge base when non monotonic information has to be handled. Maintenance of consistency may also intervene when there exists a conflict between several sources of information. This information may arise from the reasoning of various KSs or extracted from sensors.

A solution for solving these points consists in designing a truth maintenance system. At present two main approaches can be considered in this field, one with a backtracking mechanism (TMS) (Doyle, 1979), the other with parallel processing of hypotheses (ATMS) (De Kleer, 1986). In the first approach, the various alternatives associated with hypothetical data are considered and tested sequentially. The module of truth maintenance is called upon each time a contradiction is detected. It determines the minimal subset of hypotheses to be cancelled in order to restore consistency, usually by using a dependency directed backtracking technique. The main drawback of this approach lies in its inability to evaluate different competing solutions. ATMS-like systems propose another approach towards truth maintenance. This approach is based on the indexing of data by the set of hypotheses they have been deduced from, whereas TMS systems only manipulate justifications. This makes it possible for the former to explore the search space in parallel without any backtracking. Several systems have been developed, based on these ideas, for instance SHERLOCK (Cordier, 1988) which allows expressing hypotheses using the existential quantizer, thus avoiding the enumeration of hypotheses under the form of propositions.

Analysis of the application's requirements

For the AITRAS application the experts use explicitly an hypothetical reasoning scheme. The methodology of the expert follows a double approach :

• an hypothesize and test paradigm. The expert attemps to find the defaults by an iterative process of :

1) making hypotheses about the default depending on the location of the the position of the tube in the steam generator and the location within the tube,

2) finding a confirmation or an invalidation of the hypotheses made at the previous step. This second step consists in finding an explanation of the hypothetical diagnosis under the form of an aggregation of features extracted from the signal. This process follows an abductive procedure that can be implemented with an ATMS.

• a bottom up aggregation of features in order to build a qualitative description of the signal. This process can be also viewed as an hypothesis based operation. Indeed, it consist in collecting a low level description of the signal in order to build a structured description of it. All the low level features are hypothetical because of unreliability, noise and incompleteness of the signal.

The process of aggregation follows constraints expressed by experts which suppress all the inconsistent associations. This can be easily done by an ATMS the aim of which is to maintain the consistency of hypotheses.

IMPLEMENTATION OF THE SYSTEM

Decomposition of the problem into associations

As defined in the previous section, an application consists of a set of associations, each performing a distinct task and all communicating with a message passing mechanism.

In the eddy current signal interpretation problem, we identified the following associations :

low level associations :

• **real-world connection** : performs data acquisition by Eddy current probing the steam generator tubes and gives a real-time event sequence for the interpretation process.

• **signal to symbol conversion :** provides a symbolic ground for interpretation by converting signal from parametric space into symbol space, verifying the presence of some symbolic structures in the signal, and computing the degree of similarity between test signal and known defect signals. Qualitative symbols, and structured symbol representing phase, amplitude, signal timing, ratio or specific patterns are manipulated.

• **feature extraction :** builds curve description from primitive symbols, confirms the existence of a curve in terms of symmetry, segment, list of segments, lobe, complex lobes, signal to noise ratio, etc.

• **historical data base management :** provides events obtained during previous inspections.

• **expert interaction :** provides expert with comprehensible partial results and receives feedback him

high level associations :
through interaction between agents in different abstraction levels, they work out signal interpretation in terms of refined diagnosis and answer user related question.
• **elementary shape recognition** : produces some shapes out of the lobes extracted by the feature extraction association.
• **composed shape creation**, makes a signal object based on shapes belonging to different frequencies.
• **shape evolution analysis**, analyses the phase evolution of shapes through different frequencies.
• **defect identification,** according to the description of the signal in term of composed shape and evolution through different frequencies determines all the coherent diagnosis.
• **defect origin search**, try to find the origin of the defect (corrosion, shock ...), and its depth in order to make the decision to repair or close the tube.
These domains use completely different processing technologies. For the seek of execution speed, it is necessary that theses domains be distributed on several computers. Modeling these domains requires solving two problems : the multi-level representation of domain-related concepts and the active communication between different domains. The specialist society provides such a framework.

Hypothesis management

The hypothesis management provides one of the solutions to assume the connection between low level signal and pattern recognition modules on one hand and symbolic interpretation on the other. The hypotheses can cope with the uncertainty resulting from the low level analysis of the signal. Indeed, the ambiguities can be resolved by building concurrent interpretations. The constraints applied through the successive abstract levels progressively remove the uncertainty. This scheme follows a bottom up process. This hypothetical reasoning is also very powerful in managing a top down processing. Hypotheses are created from an a priori model about the signal or the diagnostic process and they are then verified by examination of the observed signal.
Hypotheses are provided both by low level and high level associations. Low level associations provide hypothetical features or qualitative symbols associated with an uncertainty measure. High level ones provide hypotheses to be confirmed by the low level.
The reasoning tool X-TRA (Charpillet, 1989) developed by our group was used with success in order to take into account the hypothetical management of the AITRAS project. It was integrated in the AITRAS architecture as a tool to encode the agents belonging to high level associations.
X-TRA can be viewed as a toolbox for truth maintenance based on TMS and ATMS techniques. The truth maintenance module of X-TRA is closely integrated into an inference engine using RETE (Forgy, 1982) and TREAT (Miranker, 1987)) compilation algorithms. Moreover, an ART ™ compatible mode is also available. X-TRA offers the possibility of encoding J. Doyle's TMS, J. De Kleer's ATMS and several extended ATMS.
The agents using X-TRA produce justifications each time a rule is activated. These justifications j can be non-monotonic. They have to be considered by the truth maintenance module of X-TRA in order to compute the domain of validity of each node n, ie the set of all environments $\{E_i(n)\}$ in which n holds. $E_i(n)$ is a set of hypotheses from which n can be derived using the set J of justifications.
The consistency of the deductions is managed association by association, thanks to specific rules called "contradiction rules". Each association provide one or several interpretations which are the maximum consistent environnements and all the deductions deriving from them. An interpretation is a partial solution with local consistency. An interpretation depending on hypotheses, can be invalidated if complementary information is provided or if its uncertainty measure becomes too weak. Automatic maintenance of the knowledge base is carried out by the truth maintenance system.

Status of the implementation

A prototype presently runs on two connected machines : a HP workstation supporting the signal processing associations and TI Explorer Lisp machine supporting the high level associations. The two machines communicate through an Ethernet local area network. We are currently rewriting all the existing lisp code in C.

EVALUATION

The evaluation is twofold : feature extraction assessment and diagnosis assessment. We have a database of 300 signals to test feature extraction. A human expert looks at lobe detection, phase and angle computation,etc. We modified the procedures until expert considered that results were correct in more than 95 % of the cases. To evaluate the entire system, we use two other databases of 400 signals hand labeled by the expert. In the first database, the number of signals of a particular kind of defect is proportional to the frequency of apparition of this defect in a steam generator. For the second database, each type of defect is represented by the same number of signals.

For each signal, we compute features and after the reasoning phase, we compare the final result with the diagnosis of the expert.Errors can be classified into two categories : slight errors and serious errors. Slight errors appear when a tube labelled without defect by the expert is classified as a bad tube by the automatic system. Such errors are easy to repair because the human expert will always perform analysis on a tube labelled "with defect" by the system.

But if the system misses a tube with defect, this is a serious error since there is no possibility to recover it. For this reason, each time an ambiguity appears we label the signal as "problem with ..." and the signal must be analyzed by a human expert.Presently, only the part of the knowledge base for signals near the tube support plate is completed. On the corresponding signals results are very good, no serious errors are encountered.

CONCLUSION

The work described in this paper concerns a generic tool for building knowledge-based system in the area of real-time signal interpretation, where no general model exists. This tool is characterized by a multi-agent architecture and a hypothetical reasoning scheme. These two points are mandatory for solving large and complex problems such as signal interpretation.

The genericity of the tool makes it possible to clearly distinguish two parts in an interpretation system , ie the application-independent part and the application-specific part. The AITRAS system uses an application-independent interpretation structure and can automatically generate a signal interpretation system once the application-dependent part of an application has been specified, avoiding rewriting application independent parts .

The system has been tested in the non destructive inspection of steam generators of nuclear plants by eddy current inspection. In addition , we are currently making extensions to the AITRAS system to deal with two other important industrial signal interpretation applications in connection with advanced maintenance of nuclear plants. The first one is concerned with heat exchanger and condenser examination by eddy current signals. The other deals with predictive maintenance of bearing elements based on vibration signals.

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Imprimé en France
par
l'Institut National de Recherche en Informatique et en Automatique

ISSN 0249-6399