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Monitoring Instrumentation Fault Diagnosis and Data Interpretation

Interprétation de données et diagnostique d'erreur dans les systèmes de surveillance

Dateninterpretation und Fehlerdiagnose bei Ueberwachungseinrichtungen

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SUMMARY

This paper describes aspects of a knowledge-based system to interpret monitoring data. There has been a large amount of work in providing systems for specific monitoring tasks, such as in nuclear power station, human and structural health monitoring. However, to date there has been little work on support for general civil engineering monitoring tasks. The system proposed is intended to provide this general support, particularly for temporary monitoring programmes. As part of this, the system provides dynamic creation of rules to deal with user-generated models of instrumentation and signal conditioning.

RÉSUMÉ

Cet article décrit un système à base de connaissances pour l'interprétation des données expérimentales. Il y a eu beaucoup de recherche pour réaliser de tels systèmes permettant l'interprétation de données spécifiques, par exemple dans une centrale nucléaire, ou pour la surveillance médicale ou structurale. Il y a cependant peu de recherches réalisées pour la surveillance générale d'ouvrages de génie civil. Le système proposé offre cette aide, en particulier pour des programmes temporaires de surveillance. Le système propose un ensemble dynamique de règles afin de maîtriser les modèles d'instrumentation et de traitement de signaux.

ZUSAMMENFASSUNG

Der Beitrag beschreibt ein wissensbasiertes System zur Interpretation von Ueberwachungsmesswerten. Umfangreiche Entwicklungen galten speziellen Ueberwachungsaufgaben wie Kernkraftwerken, medizinischen und technischen Zustandsüberwachungen, doch floss bisher wenig Entwicklungsarbeit in die Unterstützung Ueberwachungsaufgaben im Bauwesen. Dieses System ist vor allem für temporäre Ueberwachungsprogramme gedacht. Ein Bestandteil ist die dynamische Erzeugung von Regeln zur Behandlung Anwender-generierter Modelle der Instrumentierung und der Signalverarbeitung.

1. INTRODUCTION

Monitoring is becoming increasingly important within civil engineering. Given this importance, there are significant problems with the process of monitoring which must be tackled. One of the most severe problems is that of data overload. Increasing the amount of monitoring increases the amount of data produced. To be useful, this data must then be interpreted so that it can be combined with other forms of engineering knowledge. In the Department of Civil Engineering at the University of Bristol we have been developing knowledge based systems to provide support for general monitoring activities. Much previous work has been carried out on providing knowledge based systems to interpret data from specific systems [1,2,3]. The amount of effort required to produce such a system is justified where the monitoring equipment is likely to form part of a permanent structural health monitoring system, however, to date little work has been carried out on generalised techniques for interpreting signals. This would be particularly useful where temporary monitoring programmes are set up for short periods of time. However, the work is also relevant to signal interpretation for long-term monitoring applications.

This paper describes a knowledge based system (IMCES) to interpret signals from civil engineering monitoring programmes. The system has been created using Kappa PC, an object-oriented KBS development tool. The aim of this work is to provide logging systems with local intelligence and to support data interpretation. This would help to reduce the interpretation load on engineers and also to reduce the amount of raw data logged by unsupervised systems. An overview of the work and the methods used to provide general signal descriptions have been reported elsewhere [4,5]. A brief restatement of this work is included below. This paper discusses how the knowledge about instrumentation is structured and how this knowledge is used for data validation and signal interpretation.

2. INSTRUMENTATION FAULTS AND DIAGNOSIS

2.1 General

Diagnosing instrument faults can be a time consuming and difficult business. During a monitoring programme the engineer is normally working from a set of records of instrument signals. Depending on how close the engineer is to the site and what level of support is available there, he or she may also have additional information about the system. For example, weather records and verbal reports of system behaviour. However, the engineer's first point of reference is often the electrical signals recorded from monitoring instruments. It is extremely important to identify and rectify faults in the instrumentation quickly so that data is not lost. The IMCES system is being developed to assist in this task.

The first interpretation task is to identify whether the signals are displaying any unusual characteristics. This has traditionally been carried out through the engineer looking at plots of the signals and identifying unusual trends or noise in the plots. 'Unusual' in this context means different from expectations based on three sources of knowledge:

- knowledge of the output ranges and characteristics of the instrumentation used
- knowledge of the physical characteristics of the system being monitored
- experience of the characteristics of the signals seen so far

If unusual behaviour is found, the engineer will try to use other sources of evidence to explain the behaviour. For example, the reports of system behaviour mentioned above or reports of visible faults in the monitoring system. The engineer will then decide whether the signals are a true record of the system behaviour or whether they could be due to some fault in the instrumentation and signal conditioning chain. Following this, the engineer may either revise his or her ideas of the state and behaviour of the system or visit the site and perform tests on the instrumentation to try to find and rectify the fault. A summary of the process for diagnosing instrumentation faults is shown in the flow chart in Figure 1.

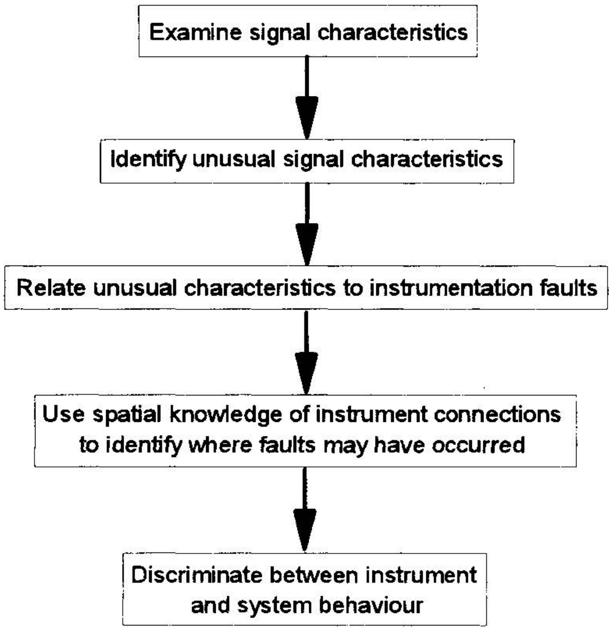

Figure 1 - Inferencing Process for Instrumentation Faults

There are clear benefits in providing some automatic data interpretation. Early automatic monitoring systems were limited to sending an alarm when the value of a particular signal crosses a given threshold. The position of the threshold would have been previously calculated from a numerical model of the system, No attempt would be made to diagnose the causes of the alarm, discern between instrument and system behaviour or draw together evidence from disparate sources. As mentioned above, work in the field of dam monitoring has tackled this issue [3]; we have been investigating the problem for use in general monitoring.

2.2 KBS Approach

We have emulated the traditional processes described above using a knowledge based system. Because the system is meant to be of general use, there are many problems to be solved. Firstly, in writing the system, we can have no knowledge of how it will be used. That is, for a given monitoring programme we do not know what types of instrumentation will be used, what types of signal conditioning will be used, how these will be connected together and what settings will be used. To overcome this problem, the user configures an object-oriented model of the instrumentation and signal conditioning as a first step in using the system.

There is a further problem in terms of the rules which will diagnose the state of the system. In a knowledge based system involved in monitoring a nuclear plant, say, all of the entities with which it has to work are known. The names of these entities can be written into the rules as the KBS is created. In our system, the rules must be created once the user has constructed the instrumentation model. It would be possible to write general rules which could access knowledge in the model at run time. However, the rules would need to follow long chains of reference through objects and would be very unwieldy. We have therefore chosen to include code to create rules dynamically as the system runs. The KBS therefore actually generates the diagnosis rules itself. These rules can then operate on the knowledge the user has entered about the types of signal, the types of signal conditioning and the connections between the signal conditioning objects. This approach also allows the rules to be linked to the objects in an object-oriented fashion. Objects in the system are responsible for managing the diagnostic rules which relate to them.

2.3 Limitations of Rule-Based Systems

A final problem is that of drawing together evidence from the signals with evidence from knowledge of the behaviour of civil engineering systems and reports of events affecting the system. The engineer-interpreter calls on information from non-signal sources to help diagnose the recorded behaviour. This information is either in the form of a model of the system or in the form of a stimulus to that system. For instance an inspection record forms a snapshot of the state of the system which can inform a crude model of the system. The model can be used to make inferences. A construction log contains both a time varying model and a record of stimuli. Weather records on the other hand are purely stimuli. This information has both spatial and temporal components which are necessary for successful interpretation. Combining these sources of information is a much larger problem because there is no accepted method of encoding engineering knowledge or representing system behaviour. Once again, in a specific application most types of event could be entered into the knowledge base. In a system for general monitoring this is not possible. A method of encoding the whole of civil engineering knowledge would be required. One approach to encoding engineering knowledge is product modelling. This attempts to provide a universal data format which "seeks to transfer the engineering intent which underlies ... graphical representations" [6]. However, product models have not yet been able to transfer knowledge between domains. It may be that we need an alternative form of representation for engineering knowledge to deal with this problem.

2.4 Knowledge Acquisition

Knowledge acquisition for the system was carried out through unstructured interviews with staff members in the Department of Civil Engineering at Unversity of Bristol, and with industrial experts in monitoring and instrumentation. Experience gained from trial monitoring programmes has also been incorporated into the system. The scope of the system is necessarily limited at present, and we aim to carry out further work to expand the knowledge base.

3. GENERAL SIGNAL CHARACTERISTICS

Signals within the IMCES system are modelled by instances of the *Signal* class. At the class level, a set of slots are defined which represent the types of characteristic the signal can have. Examples include *ConstantlyDead* and *StationaryMean*. These slots are inherited by instances of the class. The slots are of Boolean type and their values are instantiated by rules. Signal processing is carried out to calculate statistical parameters of the signals and the rules then operate on these values. A fuller explanation of this is given in [5]. Once this process has been completed each signal instance has a set of slots describing signal characteristics, each with a TRUE or FALSE value.

4. INSTRUMENTATION HIERARCHY AND FAULT INFORMATION

4.1 Knowledge Representation

Knowledge about instrumentation and signal conditioning is contained within the system. Kappa PC uses a conventional object-oriented method of knowledge representation. Variables are defined as slots within objects and may be specified at the class or instance level. Object hierarchies exist to describe both types of instruments and signal conditioning. The object hierarchy for instrumentation is shown in Figure 2.

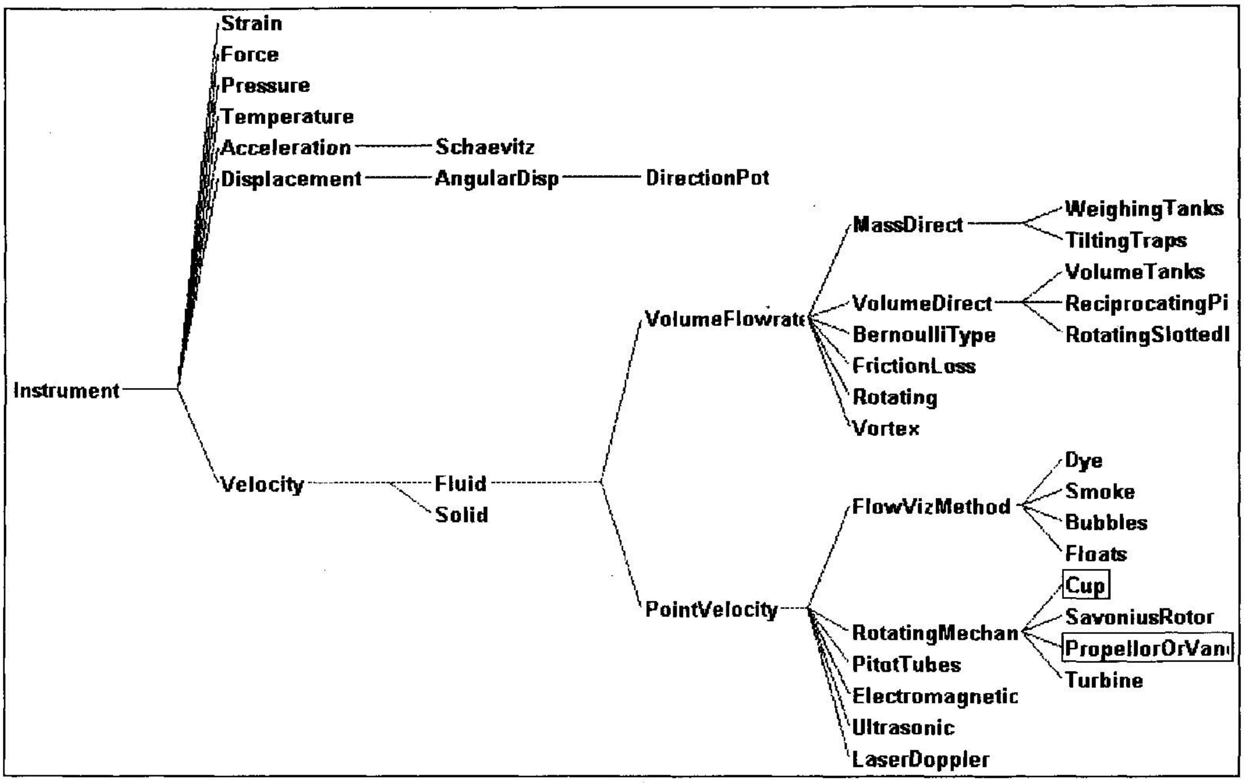

Figure 2 - Instrument Hierarchy

The hierarchy is divided according to the function and type of instrumentation. The objects within both instrument and signal conditioning hierarchies contain various kinds of knowledge:

- Signal type (pulse, analogue voltage, analogue current, digital voltage). This is represented as a slot value in the object class for each type of instrument.
- Output range and gain. This is represented as a slot value in the object class for each type of instrument.
- Expected signal characteristics. Each instrument object class contains a slot with a list of expected signal characteristics. Each signal has Boolean slots which represents whether these characteristics are true for that signal.
- Fault types and symptoms. These are represented as slots in the instrumentation and signal conditioning object classes.
- Connections between instrumentation and signal conditioning. These are represented as 'pointer' slots whose value is set within each individual instrument and signal conditioning instance. Kappa PC does not allow C++ style pointers (that is, variables which hold a memory address). The slots therefore contain the name of the connecting object and these names can be used to reference the objects.

The signal type and output range of the instruments is usually specific to each type. This is therefore defined at the leaves of the hierarchy tree. Expected signal characteristics are likely to be defined further up in the hierarchy. For example, no cup anemometers would be expected to show a negative speed, but this would not be true of all point velocity measuring instruments. The knowledge about cup anemometers therefore refines the knowledge about point velocity measuring instruments. Information about the types of fault from which instrumentation suffers may appear at a number of different levels. This is very important in a system which is meant to be generally applicable and which is expected to grow. Any new instrument which is added to the hierarchy should inherit the features of the class of instruments to which it belongs.

4.2 Rule and Knowledge Bases

An outline of the rule and knowledge bases required is shown in Figure 3. Our work so far has concentrated on the transducer, conditioning and connection rules and the instrument and signal conditioning behaviour. The inferencing process starts with examining the behaviour of individual instruments, signal conditioning units and the connections between them, shown in the centre of the diagram. Each of these may in itself be a hierarchy, for instance, there may be a number of channels passing through a filter box which need to be examined individually and then examined as a group - "do all the channels flag up behaviour x". The position rules (top left of the diagram) then use what is effectively spatial logic to examine where in the signal chain evidence of unusual behaviour occurs. The use of careful planning of the signal chain can help the interpretation process. For instance, if a system uses anemometers and accelerometers and has two filter boxes, passing half the signals from each transducer through each box will make filter box performance much easier to determine. The two ideal generalisations of this technique are firstly to provide redundant measurements by having more transducers than are needed and secondly by ensuring that each transducer signal path has a unique route through the signal conditioning chain. This will also help in the discernment between instrumentation system and observed system failure. If we can clear each item in the chain of malfunction then we can suggest that what is recorded is the actual behaviour of the monitored system.

The temporal rules (lower left) determine the time scale of behaviour. The problem of temporal reasoning is handled by dividing the signal records into windows. Within a window signal processing is used to determine whether changes in characteristics are sudden or gradual - are they step changes or drifts. The windows on the data are themselves tagged with a time stamp, so that the temporal problem is effectively transformed into a spatial one - 'is this event in front of or behind that one'. The data windows are also referenced to an event log so that unusual behaviour can be linked to reports of behaviour or faults noted in the log.

Firing the rules in this first part of the diagnosis produces evidence for examination by the rules which attempt to discern between instrumentation system behaviour and monitored system behaviour (the flow from left to right in Figure 3). Although this part has yet to be implemented some of the issues are becoming clear. While avoiding the temptation to limit the classification of behaviour to only known characteristics, there are some general rules we can apply. We have however to begin building up a hierarchical classification of civil engineering systems similar to the Instrument Hierarchy. This would include classes such as bridges with sub classes of perhaps suspension, cable stayed, glued segmental, with some further classification on size and use, such as long, medium or short span and foot, road or rail. However, this is not the only possible way of encoding the information. It may be that a representation based upon connectionist systems would be more appropriate for general use.

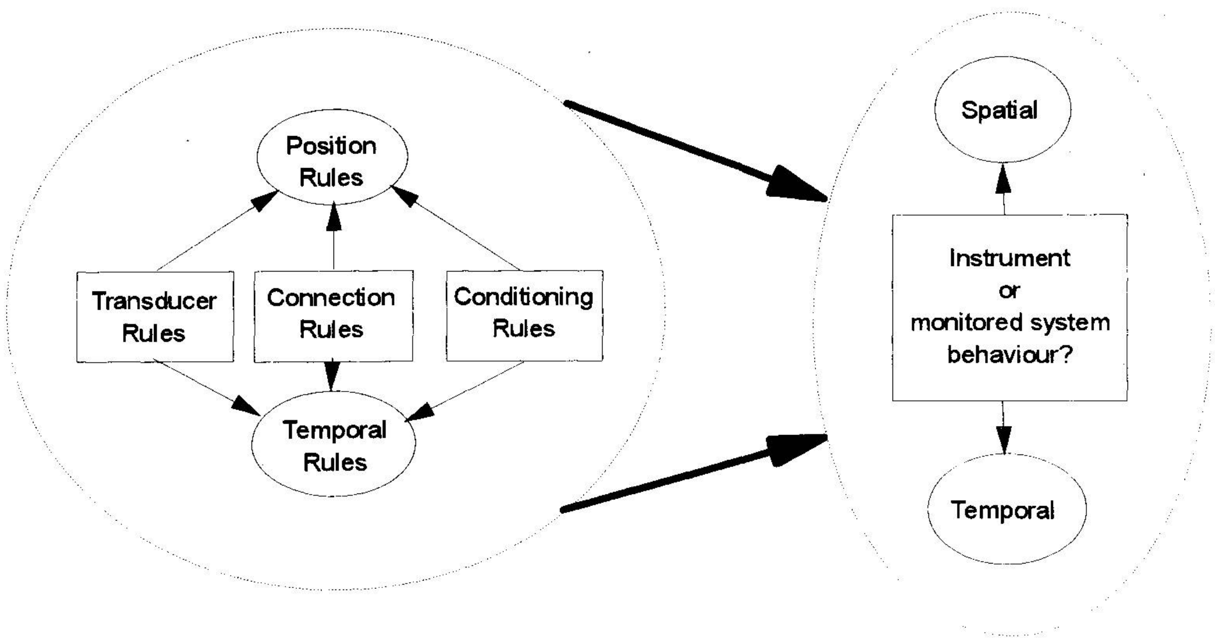

Figure 3 - Interpretation Rule and Knowledge Bases

The discernment rules will look at both frequency and time domains. We are fortunate that in the civil engineering domain the frequencies present in the systems are generally much lower than those expected in a faulty monitoring system (although faulty earthing can mislead an investigator). We can also make deductions based on the positions of the instruments. If the monitored system is actually behaving in a particular way, then several instruments will pick up the phenomenon in their own particular way. This of course again suggests that the placing of the instruments is of vital significance if we want to diagnose successfully.

As with the instruments the detection of unusual behaviour can be followed by some degree of diagnosis. If the frequency of vibration of a support cable on a cable stayed bridge drops then we can deduce that it is no longer carrying as much load. Such a database of information will take many years to build up, but it will not be superseded. It can be continually added to and made richer, even corrected as our understanding of systems improves. We must explore whether the same information can be used by those who are working on design and construction support systems. The links with product modelling in construction also need to be explored.

5. EXAMPLE

To demonstrate the inferencing process we will use an example taken from the Kessock Bridge field monitoring programme [7,8]. During the monitoring programme, a fault developed in the power supply to a filter box for some of the signals. The filters are used to remove unwanted high frequency components which can affect later signal processing. This fault manifested itself in a variety of ways including adding spikes into the signals and causing their mean level to drift and jump. One ten minute accelerometer record for the period during which the problem was occurring is shown in Figure 4.

Examination of the signal shows a clear jump in the mean level at the start of the record. The accelerometer from which this trace was taken recorded vertical movements of the bridge, and one would therefore expect the mean level to be about 1g. In practice, this offset was removed by the signal conditioning to make best use of the voltage range available. The mean level should therefore be approximately zero and a jump in the mean level is hard to explain. At this point, considerations about the behaviour of the system being monitored become important. A physical explanation for the shift could be that the accelerometer had suddenly rotated. This could be because the instrument had shifted on its mountings (unlikely) or that the bridge itself had moved (hopefully even more unlikely). A jumping mean level is therefore an unexpected characteristic for an accelerometer trace.

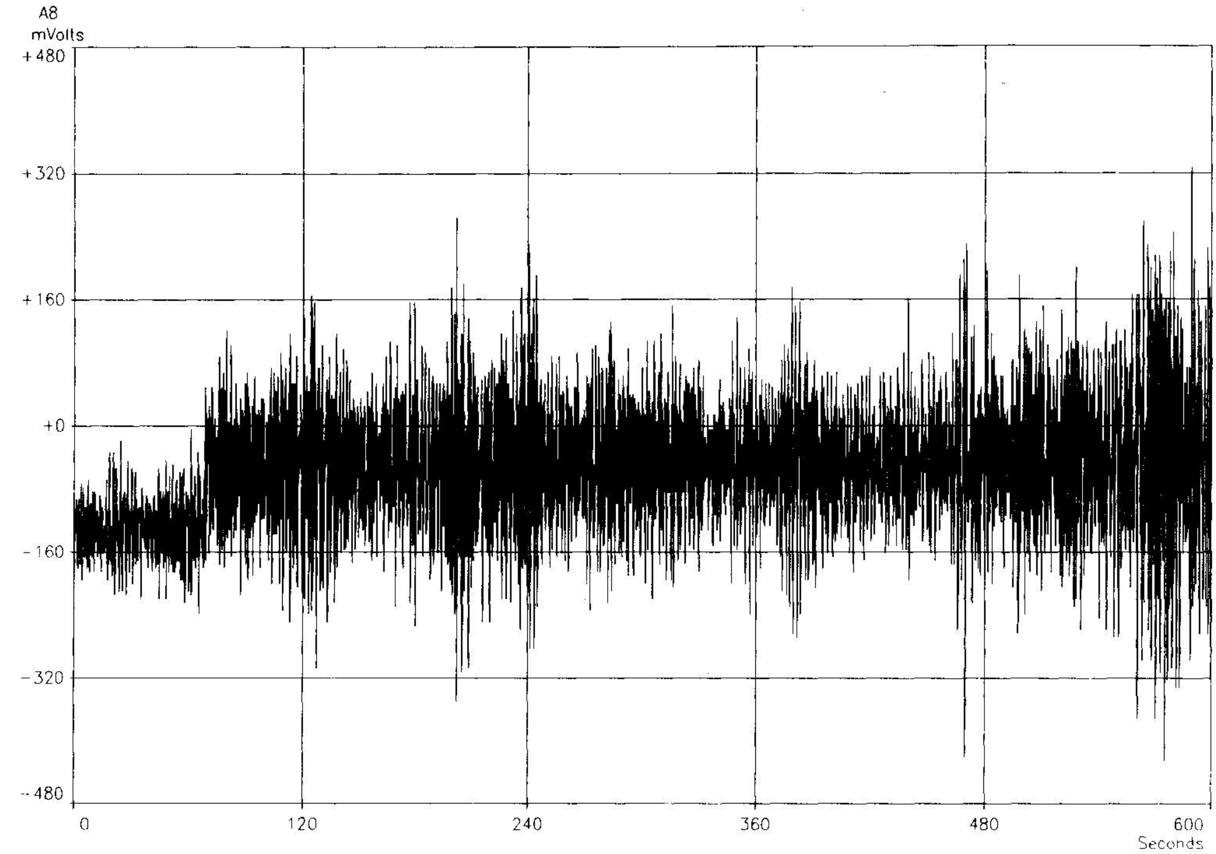

Figure 4 - Accelerometer Record Showing Change in Mean Level

As explained above, the system carries out signal processing to calculate statistical measures of the signal and the rule system then operates on these measures to assign TRUE or FALSE values to the signal characteristics. Following this, the diagnostic rules attempt to infer instrumentation faults from these characteristics. The inferencing sequence in which these rules work is shown in Figure 5. Rule names are shown in italics and the objects and slots on which they operate are shown in normal text. In Kappa PC's inferencing mechanism, when the value of a slot is altered it is placed on a list of slots for consideration by the rule base. The inferencing process therefore propagates forward until all slots have been considered or all rules have been used. The bodies of the rules operating during the inferencing process are given below.

Rule Acc1_1:
```
If GetNthElem( Acc1DatSmoBy20thDiffMaxabsrec:Values, 1 ) / Acc1Dat:Max > 0.001
Then Acc1:JumpingMean = TRUE;
```

Rule JumpingMean:
```
x|Signal: If x:JumpingMean And Not( Member?( x:ExpectedAttributes, JumpingMean ) )
Then x:HasUnexpectedAttributes = TRUE;
```

Rule SuspectChannel:
```
x|Signal: If x:HasUnexpectedAttributes Then EnumList( x:SigConChain, y, y:Suspect =
TRUE );
```

Rule SuspectSigConModule:
x|SigConChannel: If x:Suspect Then x:SigConObject:Suspect = TRUE;

Rule FilterBox1_Chan_1_1:
If FilterBox1_Chan_1:Suspect And FilterBox1:Suspect And (
FilterBox1_Chan_1:Signal:JumpingMean And Not(Member?(
FilterBox1_Chan_1:Signal:ExpectedAttributes, JumpingMean)) Or
FilterBox1_Chan_1:Signal:IntermittentlySpiky And Not(Member?(
FilterBox1_Chan_1:Signal:ExpectedAttributes, IntermittentlySpiky)) Or
FilterBox1_Chan_1:Signal:ChangeableMean And Not(Member?(
FilterBox1_Chan_1:Signal:ExpectedAttributes, ChangeableMean)))
Then FilterBox1:PowerSupplyFault = TRUE;

cc1DatSomBy20thMaxAbsRec:Values
|
Acc1_6
|
Acc1:JumpingMean
|
JumpingMean
|
Acc1:HasUnexpectedAttributes
|
SuspectChannel
|
FilterBox1_Chan_1:Suspect
|
SuspectSigConModule
|
FilterBox1:Suspect
|
FilterBox1_Chan_1_1
|
FilterBox1:PowerSupplyFault

Figure 5 - Inferencing Chain For Instrumentation Fault Diagnosis

The first and last rules in this sequence, *Acc1_6* and *FilterBox1_Chan_1_1* are created dynamically by the system at run time. They use the knowledge entered by the user in the instrumentation model. The object classes for each signal conditioning and instrumentation class contain a method which is triggered when the user completes the model. This method is essentially a template which uses the instance names entered by the user and generates the diagnostic rules. Knowledge relating signal characteristics to fault types is therefore stored implicitly within this method. The rules generated are free standing in that they are stored in the general rule base, but the instrumentation objects store the names of the rules so that they can be updated if the instrumentation model is altered. *Acc1_6* and *FilterBox1_Chan_1_1* therefore use the names of objects directly whereas the remaining rules use pattern matching to operate on all objects of a certain class.

The first rule, *Acc1_6* examines the statistical parameters of the signal shown in Figure 4 and decides that the signal has a jumping mean. The second rule, *JumpingMean* looks at the characteristics displayed by the signal and compares them with those expected. It then decides that the signal is displaying unexpected characteristics and flags this fact. The third rule *SuspectChannel* flags all channels through which the signal passes as suspect. The fourth rule, *SuspectSigConModule* flags the module containing those channels as suspect. The final rule *FilterBox1_Chan_1_1* compares the unexpected characteristic with those caused by a power supply fault and suggests that the filter box could be suffering from this fault. In practice, we would not decide that the power supply was faulty on the basis of a single channel. We would use our knowledge about all the channels in the filter box and the connections to other pieces of equipment. To improve the inferencing mechanism we therefore need to use an uncertainty handling mechanism to weigh the evidence from all the channels and assess the likelihood that a power supply fault has occurred. We are planning to tackle this stage next.

6. CONCLUSIONS

The IMCES KBS is successful in diagnosing faults in the limited domains we have used so far. However, to produce a general system we need to expand the amount of knowledge in the hierarchy and validate it against other data sets.

ACKNOWLEDGEMENTS

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A Diagnostic System with Analogical Inference and Machine Learning

Système d'évaluation avec inférence analogique et apprentissage-machine

Ein Diagnosesystem mit analogem Schliessen und Maschinenlernen

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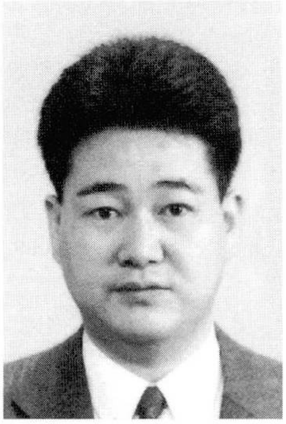

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SUMMARY

Expert systems are essential for the maintenance of existing civil engineering structures, because a wide range of expert engineering knowledge is required for such maintenance. This contribution is based on research for the development of a system to select methods for retrofitting fatigue cracking in steel bridges. Ideas for the further development of this system are presented with regard to knowledge, inference, and machine learning. Knowledge is enlarged by incorporating information concerning 75 additional cases. With this new knowledge base, the system can perform analogical inference, being equipped with an inference engine capable of greater machine learning, able to learn both positive and negative examples. The present system is capable of giving appropriate inference results.

RÉSUMÉ

Les systèmes experts sont essentiels à la bonne maintenance de constructions de génie civil, car celles-ci requièrent de grandes connaissances spécialisées. Poursuivant une recherche commencée sur l'aide au choix de moyens de réparation dans les fissures de fatigue des ponts métalliques, l'article traite d'une base de connaissances, d'inférences et d'apprentissage-machine. Grâce à 75 nouvelles études de cas, de nombreuses informations et connaissances ont pu être recueillies. Le système développé peut réaliser des inférences analogiques et prendre en compte des expériences négatives et positives. Les résultats obtenus sont encourageants.

ZUSAMMENFASSUNG

Expertensysteme sind beim Unterhalt bestehender Bauwerke besonders wichtig, da dafür ein breites Spektrum an Erfahrungswissen nötig ist. Aufbauend auf einem früheren Beitrag über die Unterstützung bei der Wahl von Reparaturmassnahmen für Ermüdungsrisse in Stahlbrücken wird die Weiterentwicklung des Systems in bezug auf die Wissensbasis, Schliessen und Maschinenlernen beschrieben. Dank 75 neuer Fallstudien und einer Inference-Maschine kann das System nun analog Schliessen und positive wie negative Beispiele lernen.

1. Introduction

Recently, the maintenance of existing civil engineering structures has become a very important subject. Since such maintenance requires engineers with ample experiential knowledge that has not yet been systematized, expert systems may be effectively used in this field.

The authors have previously developed an expert system for treating fatigue damage in steel bridges. The knowledge included in the knowledge-base was obtained from 90 cases of fatigue damage in existing steel bridges reported by Fisher(1984). To improve this system, Mikami et al.(1990, 1991) have developed an inference engine that combines a knowledge-based network model with a learning ability based on the theory of machine learning reported by Michalski et al.(1983). The learning ability is based partly on the truth maintenance system algorithm reported by Doyle(1979).

An expert system is summarized for selecting reasonable methods for retrofitting fatigue cracking in steel bridges, as reported by Mikami et al.(1994). The system uses a knowledge-based network model, which has a learning ability. The present paper reports our revision of this previous system with respect to all of its three phases; knowledge, inference, and learning.

With regard to the first phase, to complete the knowledge-base the number of actual cases of fatigue damage has been increased to 165; and this information is now used to define production relations having either positive or negative certainty factors for actual cases in the knowledge-base. The knowledge representation using the included relations is introduced, and new causal relations are generated. With regard to the second phase, the ability of the inference engine has been improved, and analogical inference is made possible. With regard to the third phase, the inference engine not only has the capability for positive learning that brings inference results closer to a positive correct answer, but also for negative learning that brings inference results closer to a negative correct answer.

2. Aim of the System

The knowledge-base, creating new causal relations, improving the inference functions, and further developing the learning mechanisms. More specifically, these improvements can be summarized as follows. We have tried to improve on the previous system reported by Mikami et al.(1994) by enlarging.

2.1 Enlargement of the knowledge-base

In the previous system, the knowledge was acquired from 90 cases as reported by Fisher, and was represented by causal relations. A causal relation was defined even if there was only a single past case to which it corresponded. The causal relation between two hypotheses was expressed using the relation from cause to conclusion. In light of these limitations in the knowledge-base, the following techniques were used to improve the quality of the knowledge-base.

2.1.1 Weighting causal relations

The previous system used four types of certainty factor represented by necessity, high possibility, possibility, or low possibility for the relations between cause and conclusion in expressing the degree of certainty with which a conclusion could be arrived at from a given cause. All the relations defined in the knowledge-base were, however, actually expressed by only one type of weight, possibility.

In the present system, the certainty factor of causal relations was weighted according to the number of cases in the collected data corresponding to a given relation, and to the year when the damage was discovered since the choice of retrofitting methods will have been made in the light of the most advanced technology at the time of discovery.

2.1.2 Handling of unknown causal relations

While in the previous system, causal relations of unknown existence are added to the knowledge-base as the knowledge that "If the condition is hypothesis A, then the conclusion is not hypothesis B", in the present system these additional relations were, endowed with a low certainty factor, because there is no information clearly denying their possibility.

2.1.3 Expression of inclusive relations

In the knowledge-base of the previous system, the knowledge was expressed as causal relations between cause and conclusion, but not between causes and other causes or between conclusions and other conclusions. In the new system, the possibility of causal relations between causes and between conclusions has been included. Consider the case where hypothesis α is affirmed and hypothesis β is also affirmed. This included relation is defined in the new system as "if α, then β is necessary". A more complex case is illustrated in Fig. 1(a). There we see that "If ζ, then η is necessary", "if α, then β and γ are both necessary", and "if γ, then δ and ε are both necessary".

2.2 Creation of new causal relations

In the previous system, a knowledge-based model was produced when reverse, inversed, and contraposition relations could be generated, as shown in Table 1, from the causal relations defined in the knowledge-base.

In the present system, however, new necessity relations are generated from the included relations there determined. For example, if included relations are defined as shown in Fig. 1(a), the necessity relations can be generated as shown in Fig. 1(b). Furthermore, for these generated relations, the reverse, inversed, and contraposition relations based on the rules shown in Table 1.

2.3 Improvement of inference functions

When observed facts are inputted, the knowledge-based model is traced. With the present system, analogical inference is also carried out, since such inference is also carried out by tracing the relations generated from these included relations.

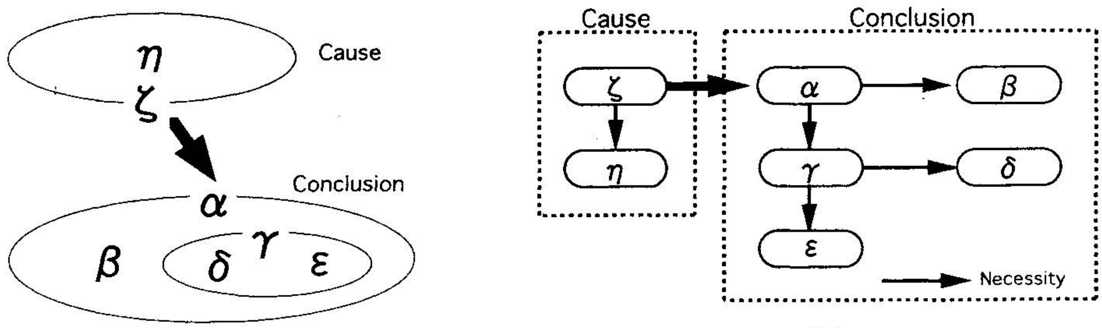


Fig. 1. Relation Generated by Inclusion Property

Table 1. Defined Relation and Generated Relation

Defined relation (1)	Reverse relation (2)	Inversed relation (3)	Contraposition relation (4)
A —N→ B	A ← P — B	Not A —P→ Not B	Not A ←N— Not B
A —H→ B	A ← P — B	—	—
A —P→ B	A ← P — B	—	—
A —L→ B	A ← L — B	—	—

Note: Certainty factors :: N;Necessity, H;High possibility, P;Possibility, L;Low possibility.

2.4 Improvement of learning mechanisms

The previous system could learn through teaching correct answers, and this learning mechanism using a teacher made possible an increase of the relations having a certainty factor between two hypotheses so as to reduce the gap between inference results and correct answers. This process is called "Positive learning".

Through such positive learning, the certainty factor of all probable relations was thus increased, and all the probable solutions obtained from observed facts were inferred. To prevent overinference, however, the new system was also endowed with "Negative learning". Negative learning can remove undesirable inference results, if an answer negating the inference results is given.

3. Arrangement and Effective Utilization of Knowledge

3.1 Causal relations having a certainty factor

By using 165 past cases of cracking, it is possible to weight the relations between two hypotheses according to proximity between the year when each of the relevant cases of fatigue damage was detected, and the number of such cases. In order to carry out this weighting, all of the relations are divided into three groups: those detected before 1969, those between 1970 and 1979, and those detected since 1980, The cases whose years of detection are unknown were placed in the first group. Each case belonging to the first group is allotted one point, each belonging to the second group two points, and each belonging to the third group three points. The cases corresponding to a causal relation are detected, and then the sum of the points allotted to these cases is computed. This total indicates the effective extent of the causal relation in question. The table shown in Fig. 2 shows the frequency of each effective extent, which is the number of the actual causal relations having each effective extent. This data can be represented graphically by taking the effective extent as the abscissa and the cumulated relative frequency as the ordinate, as shown in Fig. 2.

Because the relation between the effective extent and the cumulated relative frequency can approximate an exponential distribution, the abscissa is divided based on a geometric series. Here, the abscissa is divided by 5, 10, and 20 points, and the relations with effective extent of 1∼5, 6∼10, 11∼20, and more than 21 are defined as "low possibility", "possibility", "high possibility", and "necessity", respectively. The results of this weighting are shown in Tables 2 and 3, where the symbol → indicates the direction of relation. The Retrofitting Methods are shown in Table 4 and the Typical Joints in Fig. 3, as reported by Mikami et al.(1994).

3.2 Handling of unknown causal relations

In section 3.1, relations with effective extent of 0 represent those not borne out by any actual case. Such relations are regarded as nonexistent, and are represented in the knowledge base as relations with a negated conclusion, there being allotted to them the lowest possible type of certainty factor, that of "low possibility".

3.3 Arrangement of knowledge with included relations

In the previous system, the causes of cracking were divided into external and internal ones. Because it is possible to express these by using included relations, the causal and included relations are defined as shown in Fig. 4.

4. Improvements of the Inference Engine

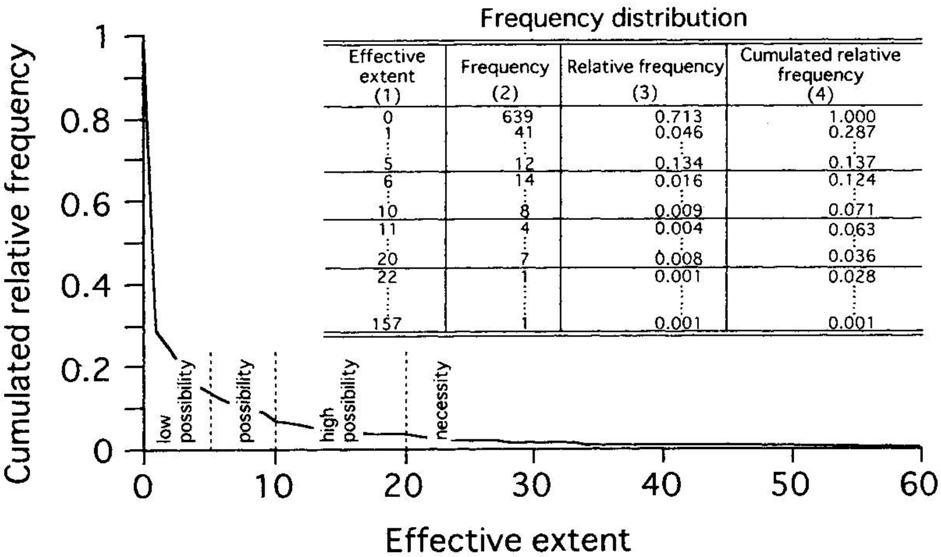
4.1 Modality interpretation

In the previous system, if both the status of a given condition and the weight of the relation were low, that condition exerted no influence upon the conclusion, when the modality interpretation was carried out. In the system, the conclusion is influenced by the condition in the manner shown in Table 5, as reported by Mikami et al.(1994).

4.2 Interpretation of included relations

If included relations are defined in the knowledge-base, it becomes possible to generate new causal relations. In the network thus constituted, causal relations between two hypotheses and relations generated from included relations are called "trunk" and "branch", respectively. When the observed facts are inputted to the constituted network, the network is traced in a manner distinguishing between trunk and branch; and, while each trunk is always traced, each branch is traced only when the tracing has been found necessary, according to the location of the fact.

For example, if a fact is inputted to γ in Fig. 1(b), the relation of "$\alpha \rightarrow \beta$" remains untraced. Because γ exists as an observed fact, hypothesis β is on same level as γ, and need not be inferred. On the other hand, both the relations "$\gamma \rightarrow \delta$" and "$\gamma \rightarrow \varepsilon$" are traced and inferred from γ. Because it is unknown whether "if γ then δ" or "if γ then ε" is true, it is necessary to trace both branches, and to carry out inference.



Effective extent (1)	Frequency (2)	Relative frequency (3)	Cumulated relative frequency (4)
0	639	0.713	1.000
1	41	0.046	0.287
⋮	⋮	⋮	⋮
5	12	0.134	0.137
6	14	0.016	0.124
⋮	⋮	⋮	⋮
10	8	0.009	0.071
11	4	0.004	0.063
⋮	⋮	⋮	⋮
20	7	0.008	0.036
22	1	0.001	0.028
⋮	⋮	⋮	⋮
157	1	0.001	0.001

Fig. 2. Relation between Effective Extent and Cumulated Relative Frequency

Table 2. Causal Relations between Causes of Cracking and Joint Action

Joint action	Cause of cracking															
	External cause of cracking											Internal cause of cracking				
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
①																
②	P	P			N	H	L		L			H	N	P	L	
③		N	L		N	N	P	L	L		P	L	N	N	P	
④																
⑤																
⑥						P								P		
⑦	L	L				L			L	L		P		L		L
⑧																
⑨								L	H			H				
⑩				L					L			L				
⑪																
⑫		P			L			L	L			P		L		
⑬					P								P			

Note : Certainly Factors :: N;Necessity, H;High possibility, P;Possibility, L;Low possibility.

Table 3. Causal Relation between Damage Factors and Retrofitting Methods

	Damage factor	Retrofitting methods																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	External cause of cracking																								
A	Vibration due to wind			L					L				L	L		L								L	
B	Live load	H		H	L				N		L		H	N								L			
C	Vibration due to earthquake																								
D	Low temperature	L						L							L										
E	Load distribution	P	H			L			N				P	L			N	P					L		
F	Defect of structural detail	N	N			L	L		N	P			P	H			P	P	L	L	L			L	
G	Secondary deformation	P											L												
H	Inferior quality of the material		L						L			L	L												
I	Welding defect	H	L	P	L			L	P		L		P	P	L							L			
J	Fabrication error																							L	L
K	Shipping and handling	P		P									L												
	Internal cause of cracking																								
L	Stress concentration	P	P	P	L			L	H		L		H	P	L	L					L	L	L	L	L
M	Secondary stress concentration	N	N	L		P			N	P			P	L			N	P	L	L					
N	Secondary stress	N		N					H				N	H											
O	Secondary stress due to buckling	L					L					L	P	P										L	
P	Residual stress																								
	Joint action																								
①	Joint action ①																								
②	Joint action ②	H	P	P	L	L			H	L			H	P		L	H	L			L				
③	Joint action ③	N	H	H		L	L		N	P		L	N	H			H	L	L	L				L	
④	Joint action ④																								
⑤	Joint action ⑤																								
⑥	Joint action ⑥																								
⑦	Joint action ⑦	L		P	L				L				L	L										L	L
⑧	Joint action ⑧																								
⑨	Joint action ⑨	L	L						L				P	L											
⑩	Joint action ⑩							L							L										
⑪	Joint action ⑪																								
⑫	Joint action ⑫				L						L		L									L	L		
⑬	Joint action ⑬								P																
	Cracking mode																								
(a)	Mode (a)	P	L						L																
(b)	Mode (b)	H		P					N	L			P	P			P								
(c)	Mode (c)	H	H	L		L	L		H	L		L	H	P		L	H	P						L	L
(d)	Mode (d)	H	L	H	L	L			P	L			P	L			L		L	L	L			L	
(e)	Mode (e)																								
(f)	Mode (f)	H		L	L				L	L			L	L		L									
(g)	Mode (g)							L							L										
(h)	Mode (h)	L	L						L				P	L											
(i)	Mode (i)				L				P		L		L									L			
(j)	Mode (j)																						L		
(k)	Mode (k)																								
(l)	Mode (l)																								

Note : Certainly Factors :: N;Necessity, H;High possibility, P;Possibility, L;Low possibility.

Table 4. Retrofitting Methods

Number (1)	Retrofitting method (2)	Number (1)	Retrofitting method (2)	Number (1)	Retrofitting method (2)
1	Stop hole	9	Welding flange to stiffeners	17	Connecting main girder with bracing
2	Gouging	10	Remelting	18	Connecting main girder with diaphragm
3	Grinding	11	Splice plate with stiffeners	19	Connecting arch rib with floor beam
4	Peening	12	High tension bolt	20	Replacement of shoe
5	Lengthening web gaps	13	Splice plate	21	Replacement of main girder
6	Extending web thickness	14	Insert plate	22	Replacement of splice plate
7	Coring	15	Tied by cable	23	New stiffeners
8	Rewelding	16	Connecting main girder with floor beam	24	Vibration proof(e.g., damper)

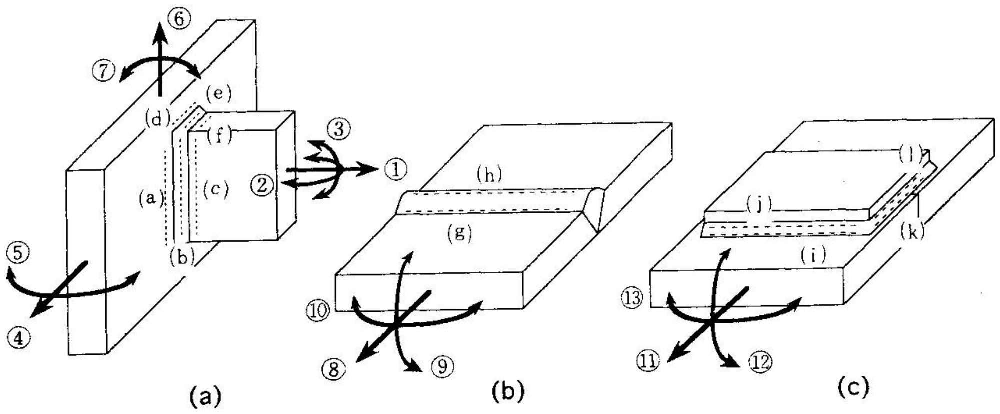


Fig. 3. Joint Action and Cracking Modes on Typical Joints; (a)Tee Joint; (b)Butt Joint; (c)Lap Joint

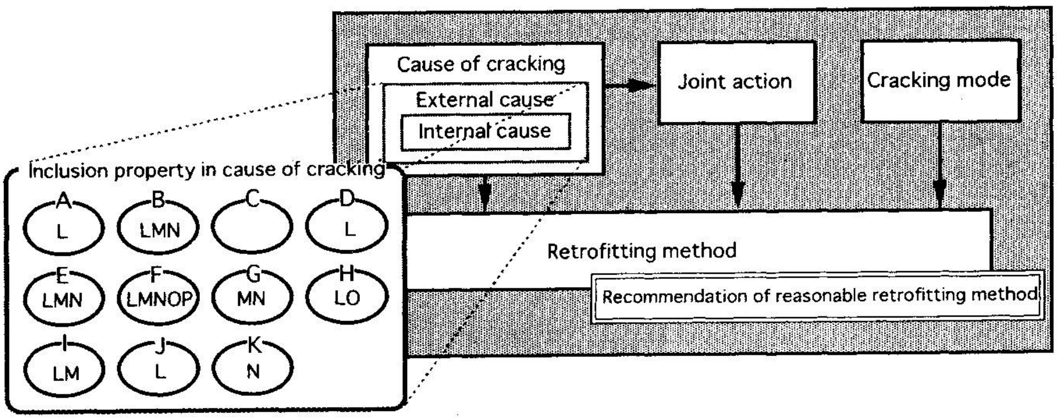


Fig. 4. A Causal Network Model for Reasoning Concerning the Retrofitting Method

Table 5. Status of Hypothesis of Conclusion

Status of hypothesis of condition A (1)	Status of hypothesis of conclusion B			
	A−N→B (2)	A−H→B (3)	A−P→B (4)	A−L→B (5)
Fact	Necessity	High possibility	Possibility	Low possibility
Necessity	Necessity	High possibility	Possibility	Low possibility
High Possibility	High possibility	Possibility	Possibility	Low possibility
Possibility	Possibility	Possibility	Possibility	−
Low Possibility	Low possibility	Low possibility	−	−
Unknown	−	−	−	−

Note : Certainly Factors :: N;Necessity, H;High possibility, P;Possibility, L;Low possibility.

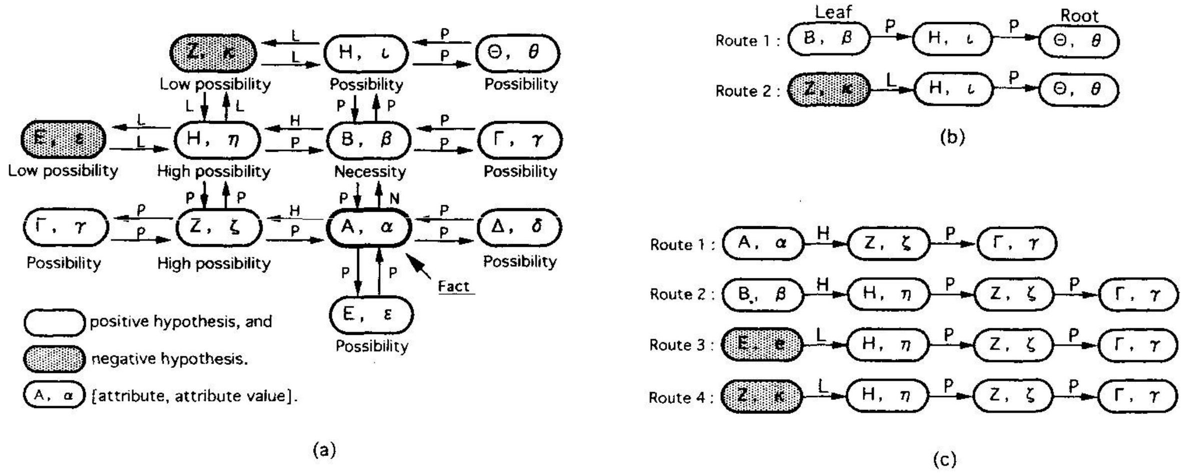


Fig. 5. Hypotheses Determined in A Network Model and Routes Obtained by Backtracking State Interpretation

4.3 Interpretation of learning with a teacher

Learning with a teacher is classified into "positive learning" and "negative learning". In the case of positive learning, the authenticity of given correct answers is positive, while in the case of negative learning, that authenticity is negative. In the case of either type of learning, it is necessary to distinguish whether the inferred hypotheses being given with the correct answer have positive or negative authenticity.

The process of learning is explained using the simple model shown in Fig. 5(a), as follows. It is assumed that a fact is inputted into the hypothesis [A, α], and then an inference result is obtained as shown in Fig. 5(a), where [A, α] indicates [attribute value].

4.3.1 Positive learning

(1) Hypotheses with positive authenticity

When a hypothesis of the correct answer is inferred as positive authenticity, the backtracking state interpretation reported by Mikami et al.(1994) is carried out from that hypothesis as the root, and the search reaching as far as the leaves. When all the leaves have been searched, the backtracking finishes. Hypotheses having the status of either fact or necessity or else terminating the network are the leaves. The route reaching a leaf with the status of either fact or necessity should carry out learning, and therefore the weights of each of the relations constituting that route are raised by one rank, those relations including ones that form part of both learning and non-learning routes. Hypotheses having either an attribute identical to that of the correct answer, or else an attribute that has already been traced once, are not retraced, as long as they have the same authenticity.

For example, let us suppose that a correct answer [Θ, θ] is given, as shown is Fig. 5(a). Because the relations extending in the rootward direction are the object of learning, as shown in Fig.5(b), two routes running from the root [Θ, θ] are to be found. And since, of these, Route 1 is that by which the learning is to be carried out, the weight of each of the relations constituting Route 1 is raised by one rank. Route 2, on the other hand, stops at the hypothesis [Z, κ], because the attribute H has already been traced.

(2) Hypotheses with negative authenticity

When a hypothesis of the correct answer is inferred as negative authenticity, a different learning process is used while the hypothesis has not yet carried out the transfer function interpretation.

Including positive authenticity, the hypothesis has positive authenticity, since this state is regarded as the root and backtracking is carried out as described in the previous section (1).

Let us assume, for example, that a correct answer [Γ, γ], as shown in Fig. 5(a), is given. In this case, since the hypotheses have positive authenticity, the states are regarded as root, and backtracking is carried out. As a result, four routes are found, as shown in Fig. 5(c), where identical attributes, [Z, ζ] and [Z, κ] are traced in route 4, because their authenticity differ.

Excluding positive authenticity, in the states preceding execution of the transfer function interpretation, no hypothesis has positive authenticity, backtracking is not carried out, and the input data and the correct answers given are stored. When identical input data are given subsequently, the stored answers are obtained immediately.

For example, let us suppose that a correct answer [Z, κ] is given as shown in Fig. 5(a). While, since the hypothesis [Z, κ] does not have positive authenticity, backtracking is not carried out, the information, "if the observed fact is [A, α], then the answer is [Z, κ]" is stored.

4.3.2 Negative learning

(1) Hypotheses with negative authenticity

When the correct answer given is taken as root, backtracking is carried out by the same process as in the case of positive learning. The route reaching a leaf with the status of either fact or necessity should carry out negative learning, and therefore the weights of each of the relations constituting that route are raised by one rank. Because the hypothesis has negative authenticity, as the weight of relations is raised, the hypothesis is more strongly negated.

For example, let us suppose that a correct answer [Z, κ] with negative authenticity is given, and backtracking is carried out. The relations composing these negative learning routes are raised by one rank.

(2) Hypotheses with positive authenticity

A different learning process is used for states preceding the transfer function interpretation, as in the case of positive learning.

Including negative authenticity, the hypothesis with negative authenticity is root, and backtracking is carried out.

Excluding negative authenticity, in the states preceding execution of transfer function interpretation, no hypothesis has negative authenticity, backtracking is not carried out, and the input data and the correct answers given are stored. Thus, when the same input data are given, the stored answers are obtained immediately.

5. A Practical Application

The present system has been applied to one actual case of retrofitting of an existing bridge, Yellow Mill Pond Bridge. The Yellow Mill Pond Bridge, a simple supported girder bridge, was constructed in 1956-1957. It was opened to traffic in January 1958. A large number of fatigue cracks developed at the ends of the cover plates. These cracks resulted from the large volume of truck traffic and the unanticipated low fatigue resistance of the large-sized cover-plated beam members. One of the main girders whose crack extended into the web was removed, and all three damaged girders were repaired with bolted web and flange splices, while minute cracks and small cracks were repaired with peening and gas tungsten arc melting, respectively.

The present expert system was executed using the observed fact. The input data given as the cause of cracking is "live load" and "stress concentration", joint action is twelve number, and cracking mode is (i). Figure 6 gives the inference result. Seven necessity hypothese were obtained with regard to the retrofitting method, while the methods actually adopted were only five. Of these seven solutions, only "high tension bolt" and "splice plate" coincide with the methods actually adopted, the other three adopted methods being obtained as only negative hypotheses of low possibility. These inference results are due to the fact that neither corresponding nor identical knowledge is included in the knowledge base.

In such a case, the system must be made to learn by teaching the actual results. First, the system is given correct answer, i.e., that the retrofitting methods are "peening", "remelting", and "replacement of main girder", and the system executes positive learning. Furthermore, because of the seven retrofitting methods previously inferred by the system, "moment plate" is undesirable, and the system also executes negative learning. The learning result is shown in Fig. 7: the required solutions are obtained by positive learning, while undesirable ones are negated by negative learning. It is able to confirm that the network is reconstructed better by the proposed learning system.

Status	Authenticity	Attribute	Attribute value	
Fact	Positive	Cause	Live load	
	Positive	Cause	Stress concentration	
	Positive	Force	Joint 12	
	Positive	Cracking	i	
Necessity	Positive	Method	Stop hole	
	Positive	Method	Gouging	
	Positive	Method	Grinding	
	Positive	Method	Rewelding	
	Positive	Method	High tension bolt	
	Positive	Method	Splice plate	
	Positive	Method	Moment plate (main girder-floor beam)	←
	Positive	Cause	Secondary stress concentration	
		⋮		
Possibility	Positive	Method	Lengthening web gaps	
		⋮		
Low possibility	Negative	Method	Peening	←
	Negative	Method	Remelting	←
		⋮		
	Negative	Method	Replacement of main girder	←
		⋮		

Fig. 6. First Inference Result for Yellow Mill Pond Bridge

Status	Authenticity	Attribute	Attribute value	
Fact	Positive	Cause	Live load	
	Positive	Cause	Stress concentration	
	Positive	Force	Joint12	
	Positive	Cracking	i	
Necessity	Positive	Method	Stop hole	
	Positive	Method	Gouging	
	Positive	Method	Grinding	
	Positive	Method	Peening	←
	Positive	Method	Rewelding	
	Positive	Method	Remelting	←
	Positive	Method	High tension bolt	
	Positive	Method	Splice plate	
	Positive	Method	Replacement of main girder	←
	Negative	Method	Moment plate (main girder-floor beam)	←
		⋮		
Possibility	Positive	Method	Lengthening web gaps	
		⋮		
Low possibility	Negative	Method	Extending thickness	
		⋮		

Fig. 7. Inference Result after Learning for Yellow Mill Pond Bridge

6. Conclusions

In this study, we have enlarged the knowledge-base and improved the inference and learning capablities of our expert system for selecting retrofitting methods in cases of steel bridge fatigue damage, as previously reported by Mikami et al.(1994).

First, to complete the knowledge-base, causal relations were weighted according to the year when each relevant case of fatigue damage was detected, and the number of cases detected. Causal relations of unknown existence were defined as relations with negated conclusion, while those impossible of definition by causal relation alone were newly expressed using included relations. Analogical inference was made possible by generating new relations from included relations. Not only positive learning, by which the inference results are brought closer to correct answers, but also negative learning, by which undesirable results are removed, were made possible. The improved system is far more capable of deriving probable solutions from observed facts. Frequent usage of its positive and negative learning ability will further refine the knowledge.

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Computerised Support for the Management of Buildings in Service

Support informatique pour la gestion des bâtiments en service

Ein Computerprogramm für die Erhaltung von bewohnten Gebäuden

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SUMMARY
A system is presented which supports the knowledge process of a building and manages not only ways for setting the knowledge but also the knowledge itself; thus it is a system that assists the operator responsible for the maintenance of the building. In its general configuration, it is a complex system made up of multiple hardware and software interacting one with another. The main core comprises a software system which assists the expert in three fundamental activities: 1) Consultation of the characteristic elements of the domain (activities, agents, information, tools, archives) and of their relations; 2) Preparation of the Building Computerised Card through retrieval and elaboration of information relative to buildings under investigation; 3) Consultation of the card containing information relative to specific buildings.

RÉSUMÉ
Le résultat de la présente recherche est un système à base de connaissance pour un bâtiment; il gère aussi bien les modalités nécessaires pour obtenir la connaissance que la connaissance elle-même. Le système assiste le spécialiste responsable d'une maintenance correcte. Ce système complexe se compose de différents matériels et logiciels interactifs. Le noyau principal se compose d'un système logiciel qui assiste le spécialiste dans les trois activités fondamentales suivantes: 1) consultation des caractéristiques du domaine (activités, agents, informations, instruments, archives) et leurs relations; 2) préparation de la fiche informatique du bâtiment par la recherche et l'élaboration des informations concernant les bâtiments étudiés ; 3) consultation de la fiche d'information sur les bâtiments-types.

ZUSAMMENFASSUNG
Die komplexe Systematisierung des Erhaltungsprozesses führte zu einem Computersystem, das den Kenntnisprozess eines Gebäudes unterstützt, indem es sowohl die Erkenntnisgewinnung als auch die Kenntnisse selbst verwaltet. Der Hauptkern besteht aus einem Softwaresystem der Originalplanung, das den Fachmann bei folgenden drei grundlegenden Tätigkeiten unterstützt: 1) Beim Nachschlagen (Konsultation zur Kenntnisnahme) der charakteristischen Elemente dieses Sektors (Tätigkeiten, Agenten, Informationen, Instrumente, Archive) und ihrer Beziehungen; 2) Erstellung der Computerkarte des Gebäudes mit Hilfe der Einholung und Ausarbeitung von Informationen über die zu untersuchenden Gebäude; 3) Das Nachschlagen der Karte, die die Informationen über spezielle Gebäude enthält.

1. INTRODUCTION

In the last few years, the rescue interventions on the existing, deeply degraded building patrimony have increased as a consequence of the consciousness of its historic, artistic, environmental and economic value [1]; this has brought about a strong thrust to the research field concerning techniques and diagnostic tools to be used in order to reset the prefixed quality levels of the building; on the contrary, the methodological aspects of the rescue have not been developed likewise. The interventions of building rescue must be considered as processes in which are to be defined all those activities to be carried out, their temporal sequence, tools to be used, involved operators, i. e., methodologies to be applied for the rescue and/or building *maintenance*.
The present work [2] puts forward, in the very general context of the BUILDING RESCUE (Fig. 1), a system analysis of the **Recovery** process as defined by the Italian law no. 457/1978 [3].

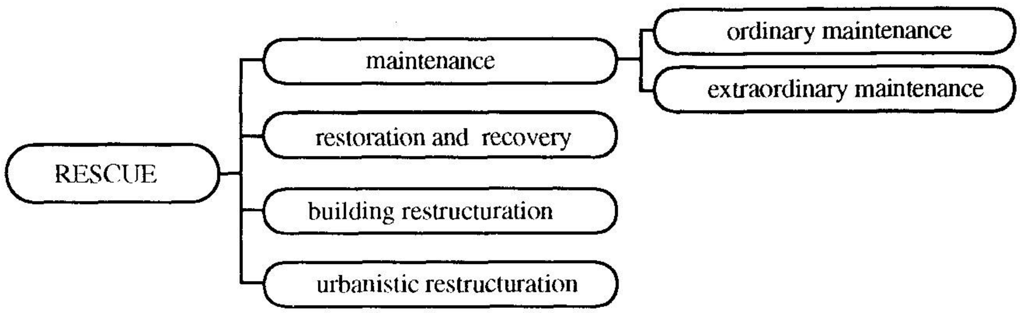

fig. 1 The rescue process

The four foundamental stages which constitutes such a process have been singled out, defined and are as follows:
A- Pre-project stage: the building knowledge.
B- Planning stage: the project of interventions for building recovery.
C- Implementation stage: the interventions for building recovery.
D- Building maintenance stage.
The present research has investigated the *knowledge stage* which is deemed essential for the proper implementation of the recovery process. Moreover, a computerized system, referred to as SMIRNE with the italian acronym (System for Intelligent Methodological Support of Building Rescue) has been set up. The system supports the knowledge stage of building by handling both the modalities to obtain the knowledge and the knowledge itself: thus, it is a system that assists the expert who is involved in the pre-project stage of the building knowledge and must either carry out recovery interventions or operate for the proper building maintenance.

2. THE BUILDING KNOWLEDGE STAGE

The *knowledge stage* is becoming essential also in the new building processes, because it is recognized that important information on the building is not to be lost even in the constructive stage.
The knowledge stage makes possible to elaborate, at the same time, the various stages (planning, implementation and building maintenance) and the complex of structured information, which constitutes the Building Computerized Card (B.C.C.). Only the exact knowledge of the building in its historical, technological and functional specificity (constructive techniques, materials, technological systems, construction age, destination, alteration, urbanistic bounds, etc.) allows properly oriented interventions, when necessary, and timely arranged interventions for the maintenance. It is a straightforward building anamnesis [4] which becomes a methodological tool of analysis.
Information is thus used in relation to specific goals to be attained, the knowledge goals being different and various:
- historical and cultural goals (catalog of buildigs and architectural masterpieces, etc.);
- fiscal goals (cadastral enrollment, real estate taxes, solid waste disposal taxes, etc.);
- public administrative goals (rescue plans, construction authorizations, adjustment to safety codes, etc.);
- maintenance goals (maintenance booklet, calculation of millesimal portions, etc.);
- others.

The building knowledge stage unfolds into planning of activities to be carried out and into definition and execution of corresponding actions:
- planning makes use of description or selection of activities and definition of archives, agents and information to be gathered:
- execution makes use of a series of activities, managed by specific professional profiles and aimed to collect, elaborate and retrieve documents and data from the various available information sources (archives).
The main information sources are the building itself and all documents that accompany the building from its inception until its demolition, a life cycle that may last centuries. All pertinent, documental information deserves to be searched, collected, organized and stored.
The knowledge objective is the preparation of an information assembly (BUILDING COMPUTERIZED CARD-B.C.C.) made up by the totality of information (documents and data [5]) relative to the investigation object, which can be aggregated in distinct cards, and which are related to defined levels and specific investigation spheres.
Two levels, often interrelated, are to be considered: the territorial level (urban context, environmental conditions, etc.) and the building level (morphology, constructive techniques, etc.).
The essential investigation spheres are locational, juridical-urbanistic, historical, geo-topographical-cadastral, typological-morphological, tecnological-constructive, tecnological-plants, functional-environmental.
- Data relative to the individual building are gathered from the <u>locational sphere</u> and allow its immediate location with respect to the administrative-territorial organization.
- Data relative to the building property and regulation bonds, and to the operators responsible for its planning, construction and management in service, are gathered from the <u>juridical-urbanistic sphere</u>.
- Data relative to the construction cronology *from a remote limit to the recent limit* [6] are gathered from the <u>historical sphere</u>.
- Data relative to the building location on the territory and to the cadastral division, are gathered from the <u>geo-topographical-cadastral sphere</u>. Such data are also useful for the evaluation of the urban context.
- Morphological-dimensional data for a type classification, relative to predetermined typological classes, are gathered from the <u>typological-morphological sphere.</u>
- Data relative to the physical elements of the building tecnological system, i.e., constructive systems, components, semicomponents as well as materials, are gathered from the <u>tecnological-constructive sphere</u>.
- Data relative to the mechanical and electrical systems (heating, lighting, ventilation, electric, waterworks, sanitary fittings, etc.) are gathered from the <u>tecnological-.plants sphere</u>.
- Data relative to the qualitative and quantitative status of spaces and their use are gathered from the <u>functional-environmental sphere</u>.
The knowledge stage articulates within such spheres in activities and subactivities (Fig. 2), carried out by agents, by means of specific tools, aimed to the singling out, retrieval and/or elaboration of information useful to create what we have called the Building Computerized Card (B.C.C.). The research unit, after having singled out the activities to be performed, has deemed essential to elaborate, with the support of computerized tools, a system able to handle activities aimed to acquire knowledge, in order to prepare the Building Computerized Card (B.C.C.).
The activities planning requires, first of all, the identification of:
- information to be retrieved (documents and/or data),
- archives to be consulted,
- agents with specific professional expertise.
These concepts: Activities, Agents, Tools, Information (Document and Data) and Archives are linked by relationships as follows:
the <u>Activities</u> are processes capable of accepting Data and/or Documents, manipulating them and outputting again Data or Documents;
the <u>Agents</u> are, in general, people (e.g. the user, the planner, the historian, the physicist, etc.), and have the task to carry out the Activities;
<u>information</u> is any set of information which must be found or produced during the various Activities. Certificates, cartographies, regulations, to be found in agencies and libraries, as well as papers elaborated by the planner or by any other agent, fall within this concept;
the <u>Archiv</u> is the original source of information (Documents and Data). For example, it can be either a traditional archiv, (as Municipal Archiv, General Land Office Archiv, etc.), a data processing center, or a library. A peculiar Archiv and always at hand is the building itself;

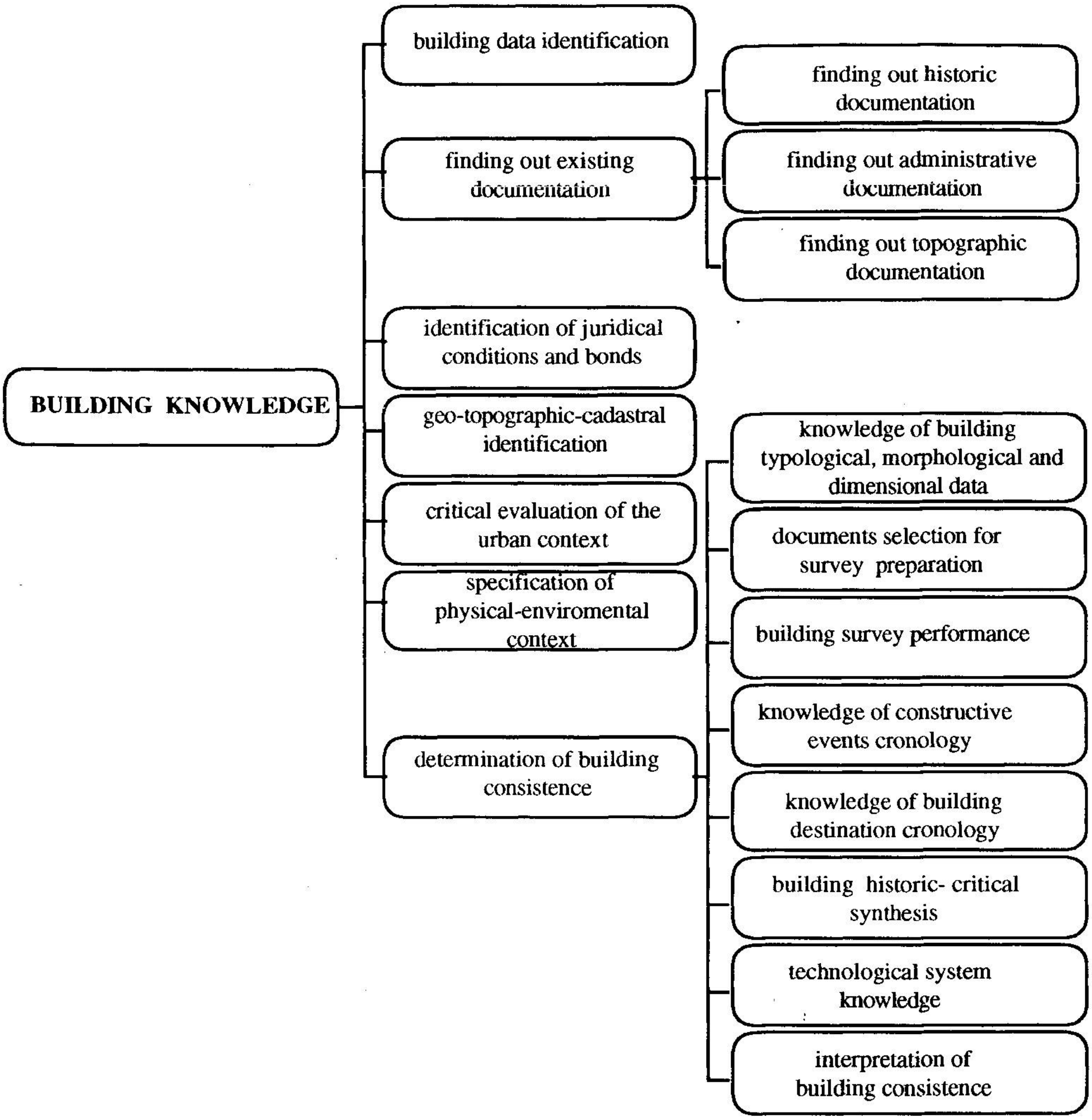

Fig. 2 Taxonomy of activities aimed to knowledge acquisition

the Tools support the Activities. They can be of various types, and can be classified either as traditional tools and innovative tools, or as mechanical tools, electronic tools and computerized tools.

3. GENERAL CONFIGURATION OF THE SMIRNE SYSTEM

The SMIRNE system, in its actual configuration, is a complex system made up by multiple hardwares and softwares interacting one another (Fig. 3).

The main core of SMIRNE is made up by a software system, developed by us with a Prolog language, which runs on a Macintosh PC; the SMIRNE System and assists and guides the expert in three foundamental activities:

1) Consultation (to obtain information) of the characteristic elements of the domain (Activities, Agents, Information, Tools, Archives) and of their relations.
2) Preparation of the Building Computerized Card (B.C.C.) through retrieval and elaboration of information relative to buildings under investigation.

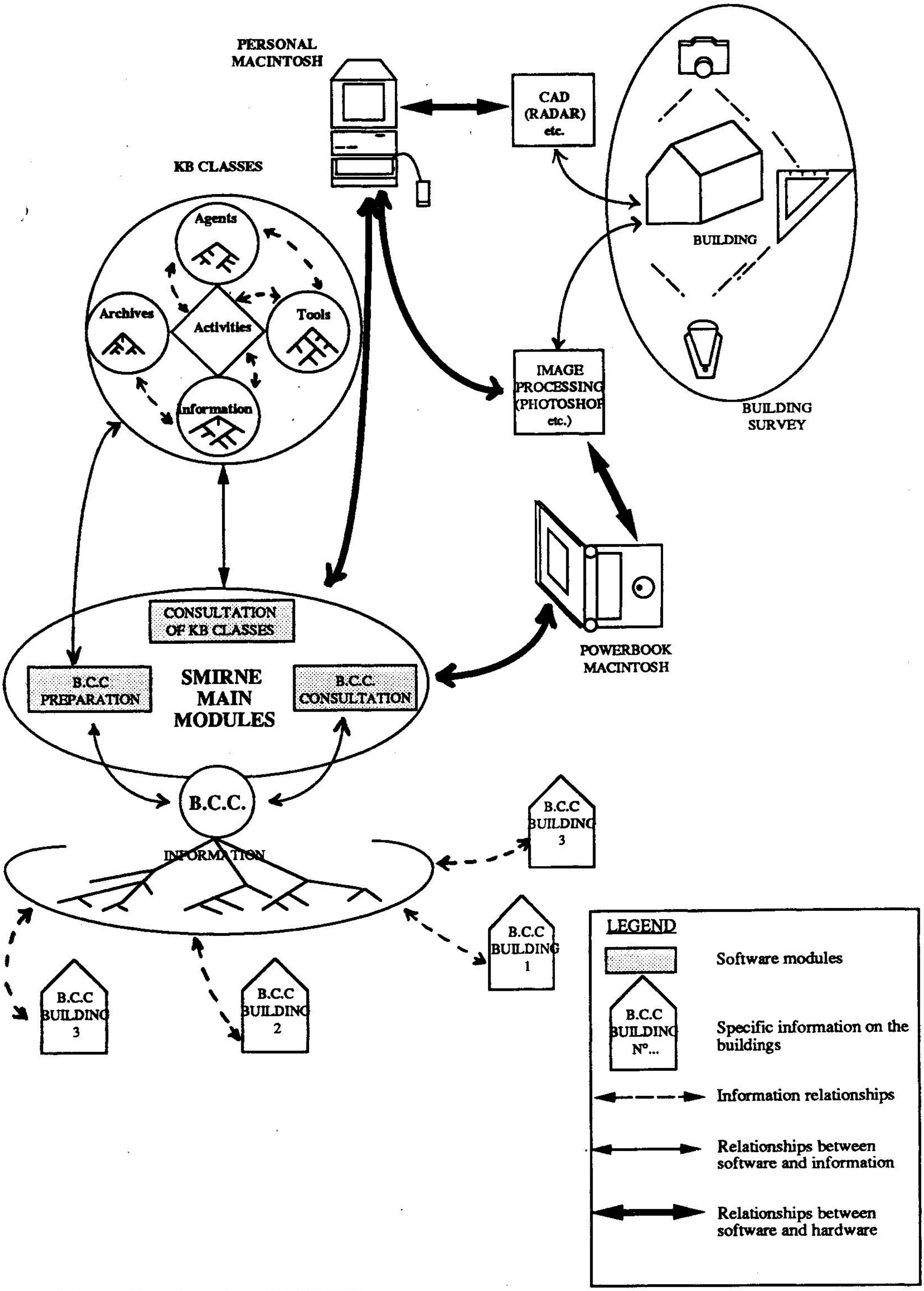

fig. 3 General configuration of SMIRNE System

3) Consultation of the Building Computerized Card (B.C.C.) containing information relative to specific buildings.
The software implemented in Prolog allows:

1. Navigation in the semantic network of concepts (Activities, Agents, Information, Tools, Archives) and of their relationships.
2. Navigation in the information archiv of the Building Computerized Card (B.C.C.).
3. Management of the various phases involved in the execution of activities for the building knowledge (information retrieval, agents and tools collection, activities elaboration, storage of information in the Building Computerized Card (B.C.C.).

The SMIRNE core is made up by an 'inferential system' ('inferential motor') and a knowledge basis of the domain elements (Building knowledge for its rescue) and their relations.
Additional software and hardware elements, supporting the principal core, are used for the filing of physical information (texts, bidimensional images as either ruster or bit maps) as well as for information retrieval. CAD softwares (Radar, etc.) residing in the personal computer, are used to develop tridimensional models of the building under consideration.
Additional softwares which handle bidimentional image (Photoshop, etc.) are used, with cameras, videocameras and scanners, to develop bidimentional images of the building or digitize hardcopies drawings.
Such programs which handle bidimentional image are also used to convert tridimensional and bidimensional drawings in unified formats for filing in the Building Computerized Card (B.C.C.).
For retrieval of various information filed in the Building Card are needed hardwares such as printers and plotters.
In summary, the SMIRNE core is used as a support (supervisor) to all activities in preparation of the Building Card and in consultation of the domain elements of information contained in the card itself; specific softwares (Radar, Photoshop, etc.) are needed to develop tridimensional models of the building and for the high quality visualization of images (colour, high definition, etc.) and, in general, for manipulation of tridimentional models.

3.1 Development modalities of SMIRNE system

The actual version of the system has been developed in the following stages:

stage1: theoretical development of the model of the Building Knowledge System (inferences on network classes, preparation of the Building Computerized Card B.C.C., consultation of the Building Computerized Card B.C.C.);
stage 2: complete taxonomic description of activities for the building knowledge;
stage 3: complete description of the concepts of Information, Agents, Tools, Archives;
stage 4: Prolog implementation of the concepts description and of the concepts relation;
stage 5: examination of the building as a typical example; retrieval of textual and graphical information and their filing;
stage 6: Prolog implementation of the system for the building knowledge in its three articulations (Inferences on classes network, preparation of B.C.C., consultation of B.C.C.).

Such stages are developed by specific figures of the research staff:
- the domain expert, i. e. the expert in the recovery field,
- the system expert, i. e. the expert in the planning of computerized knowlwdge systems,
- the graphic expert, i. e. the expert in the computerized preparation and handling of graphical systems.

Each stage is developed by only one, or more, of the mentioned experts.

4. THE SYSTEM MODEL

The model of the building knowledge system is made up by three main inferential modules (Fig. 4):

1 - the module of INFERENCE ON THE NETWORK OF CLASSES OF CONCEPTS (Activities, Agents, Information, Archiv, Tools), that consists in a 'navigator' of the semantic network whose nodes are: Activities, Agents, Information, Archiv, Tools;
2 - the module of the Building Computerized Card (B.C.C.) PREPARATION, that consists in the overall procedures for performing activities linked to the building knowledge, therefore, retrieval of given information, its elaboration and filing in the Building Computerized Card (B.C.C.);
3 - the module of the Building Computerized Card (B.C.C.) CONSULTATION, i.e. retrieval or either simple or

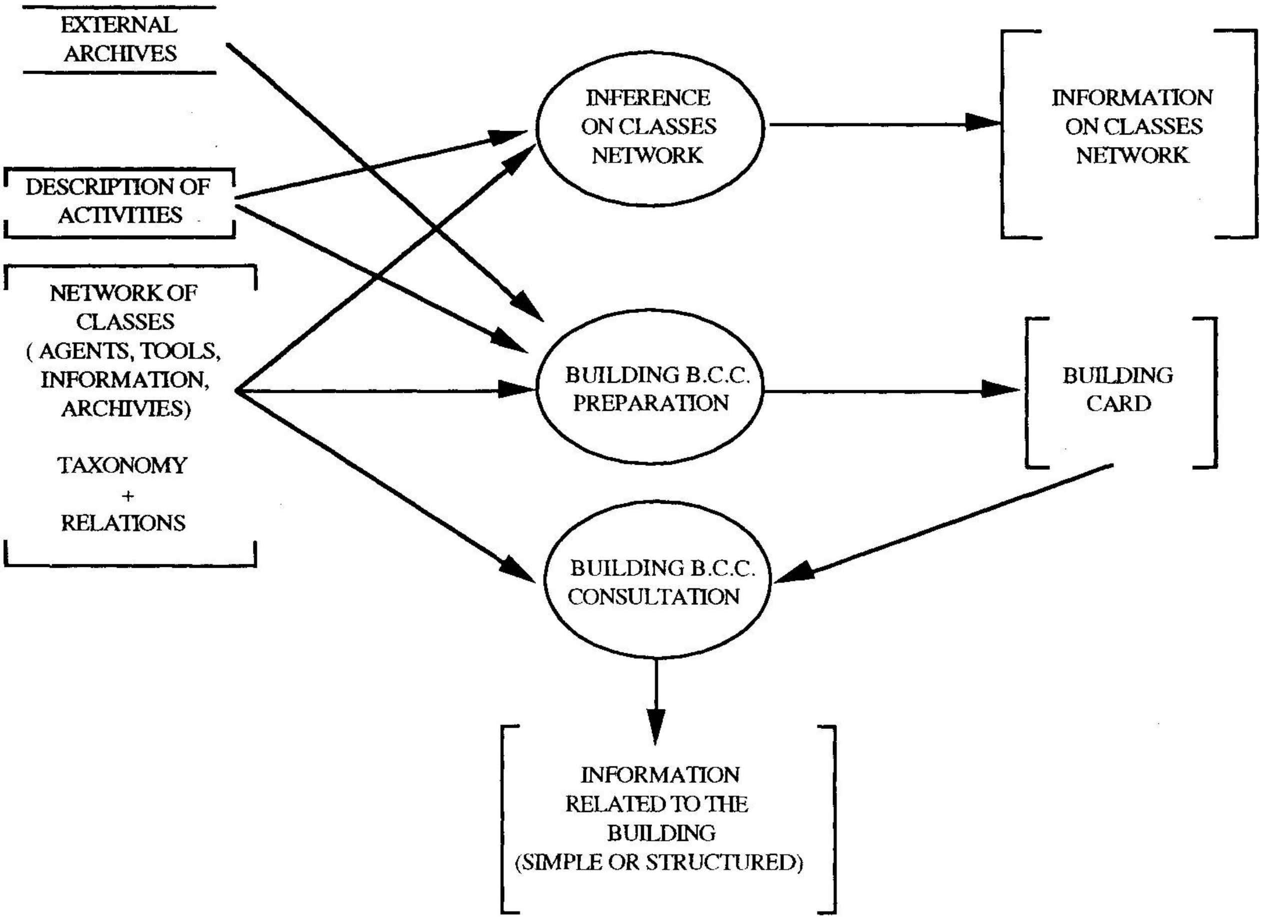

fig. 4 Main inferential cores of the system model

structured information of the building knowledge in order to prepare specific documentation useful for the subsequent recovery phases.

The *knowledge sources* that support such inferences are:

1 - the EXTERNAL ARCHIVES which provide information required for the preparation of the building card;

2 - the DESCRIPTION OF THE BUILDING KNOWLEDGE ACTIVITIES required for the inferential module on the network of classes and for the module of building card preparation;

3 - the NETWORK OF THE BUILDING KNOWLEDGE CLASSES, or else the description of the classes of agents, tools, information, archives, in their taxonomies and relationships, required for the module of network inferences, for the module of the building card and, in one of its subsystems, for the module of card consultation;

4 - the BUILDING COMPUTERIZED CARD (B.C.C.) produced by the central module of the knowledge model and required for the consultation stage on the building information.

In the preparation of the Building Computerized Card (B.C.C.), each single action is made up by three substages:

1 - preparation

2 - elaboration

3 - filing

In the **preparation stage** one or more agents are involved, one or more tools are recalled and the information required for the elaboration is retrieved, trough a given archiv.

The **elaboration stage** is the fundamental core of the action execution: the input information is manipulated by the agent by means of tools and additional information is produced as result of the elaboration.

The **filing stage** consists in the filing of produced information into the Building Card archiv and in the update and of the system advancement status (list of the actions carried out at that time).

4.1 The structure of the Building Computerized Card (B.C.C.)

The structure of the Building Computerized Card B.C.C. is a tree structure having the information concept at the root and taxonomic branching of this concept (from classes to subclasses) (Fig. 5).

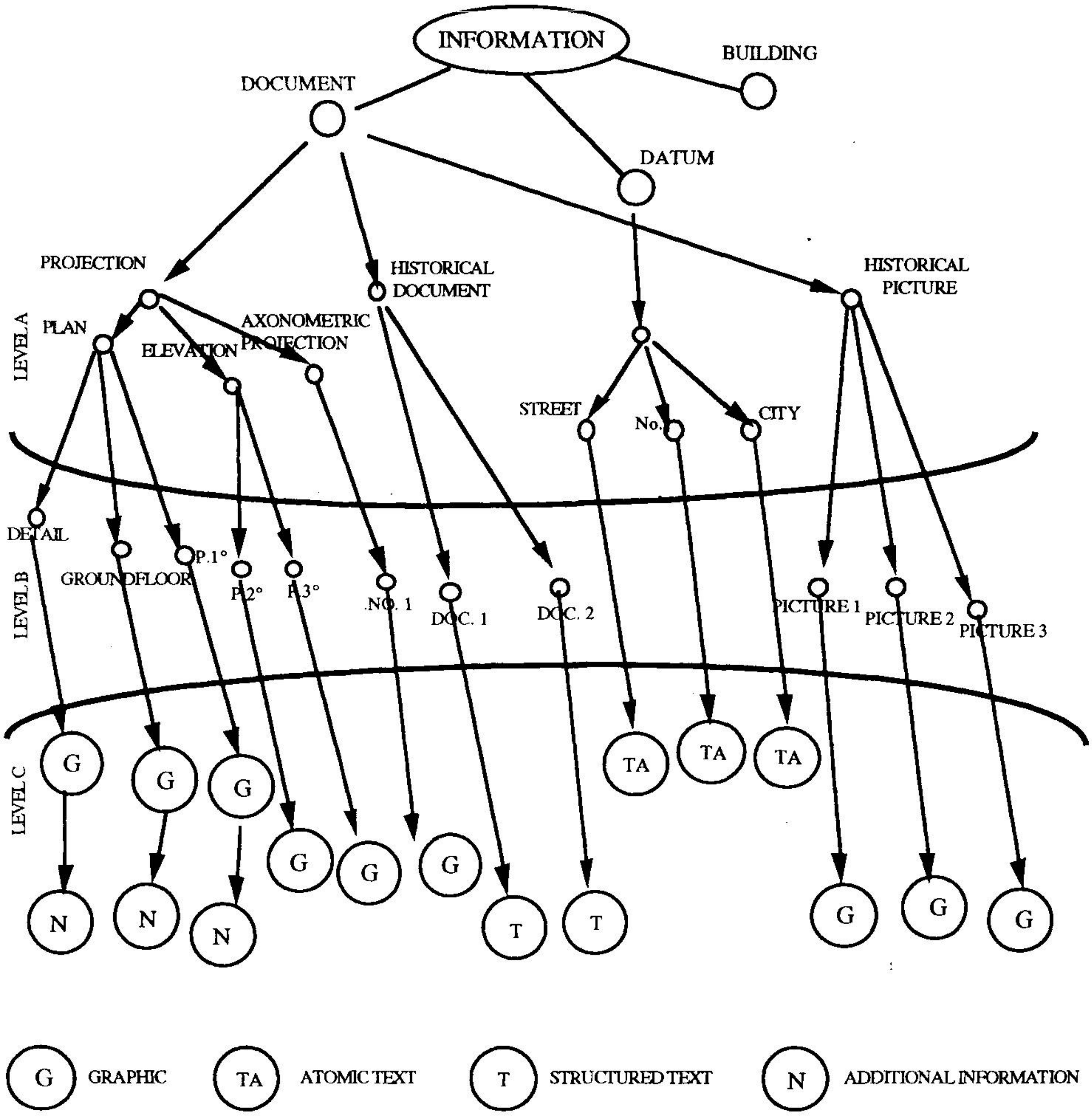

fig. 5 Tree structure of the Building Computerized Card (B.C.C.)

Such a branching begins with the 'generation', from the 'information' concept, of the two descending concepts 'document' and 'datum', and goes on, from primary concepts to descending concepts, until it reaches the leaves ('terminal' information). This part of the card structure (always present) is common to each building and constitutes the first level (starting from the top) of the structure itself (in an ideal division through levels, from general to particular). General 'Terminal' information, in general, terms may give origin to specific information which may vary for each given building; or else they can be related directly to 'physical' information. That part of the card structure which corresponds to 'specific' information constitutes the second level of the structure itself. 'Comment' information may be related to phisical information. Both 'physical' information and 'comment' information are situated to the third level of the card structure.

5. IMPLEMENTATION CHOICES

Smirne is made up baisily by three parts (foundamental functions):
I. Management of a semantic network of concepts and relationships on the knowledge for the building recovery.
II. Management of a collection card of the building information, structured as a tree.
III. Management of the preparation of the building information card (prepared through the activities development).
These three parts are implemented in Prolog.
For the fullfillment of parts I and II, we could have also used either a relational DBMS (Data Base Management System) or an ipertextual environment; on the other hand for the fullfillment of part III, it was necessary the use of a programming language with procedural characteristics.
It has not been possible to interface properly a DBMS or an ipertext with the procedural program required for the part III.
Therefore, Prolog has been the optimal solution in this case.

6. CONCLUSIONS

SMIRNE, in its actual configuration, can support the building knowledge stage which is made up by:
Activities: Activities to be performed for the building knowledge and the formation of the building card.
Agents: Agents that perform activities.
Tools: Tools (manual, mechanical, electrical and electronics, computerized) that, used by agents, support activities.
Information: Documents and data (textual or graphical) that are needed either to prepare the computerized card, or to flow directly into the card.
Archives: Sources of information (places where information is retrieved).
The SMIRNE system can be enlarged in order to favour a better articulation of building knowledge elements and a better articulation of the knowledge consultation, so that it may allow particular 'navigations' within such a knowledge and extrapolation of 'relational' knowledge (among different objects-buildings too).
Enlargement of the structural possibilities implies changes of the intrinsic SMIRNE structure in order to let SMIRNE handle not only support of knowledge (and executive) activities, document preparation (e.g. the Building Card) and document consultation but also the functioning of software and expert sistems.
SMIRNE, in its actual configuration, is ready to support the building knowledge stage and the building recovery; it will allow the preparation of computerized cards for the knowledge of different buildings.
SMIRNE can be also used for more general aims, i.e. for the building recovery and for any situation where it is needed the 'knowledge' of the building of a specific city (or province, region, etc.), regardless of aims of such a knowledge (e. g., description of the architectural patrimony of any type) or for specific aims such as building maintenance.
Nowdays the SMIRNE System users' could be the involved operators in recovery activity: designers, historians, technical-physicist, topographers, building administrators or owners; each one of them can, inside SMIRNE, enter or utilize information relative to the building under examination.

ACKNOWLEDGEMENTS

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NOTES

[1] The European Charter of the architectural patrimony, promulgated at the end of the European Architectural Patrimony Congress, held in Amsterdam in 1975, and adopted by the committee of the European Council Ministers, states: "The European building/architectural patrimony is formed not only by the most prestigious monuments, but also by all the

buildings which make up our cities and our traditional villages in their natural and constructed environment (...) For quite some time, only the most important monuments have been preserved and restored, regardless of their context. They may, however, lose a great deal of their value if their context is altered. Moreover, groups of buildings, even without outstanding architectural features, may have environmental qualities which contribute to give them a diversified and articulated artistic value. These groups of buildings must be preserved as such."
Such a principle is recalled by the Italian law 457/1978 which specifies in the Fourth Title the General Rules for the rescue of the existing urbanistic and building patrimony; in the article 31 of this act, ordinary and exstraordinary maintenance, restoration and recovery, building and urbanistic restructuration fall within the interventions aimed to the building rescue. They are not simple interventions but specific processes characterized by specific, common aspects: the preexistence of the constructed object which must be investigated, measured, checked, i. e. known in-depth, before starting any building activities.

[2] This paper is the second in a series. The first one was published in "Knowledge-Based Systems in Civil engineering", IABSE Colloquium, Beijing, 1993, pp. 301-310. (Reference no. 2)
This work is part of "Progetto Finalizzato Edilizia" (Targeted Project for Building), funded by the National Research Council, the main Italian Research Body. The research program, started in 1989 lasts five years. The Project articulates into an experimental area and three subprojects each pertaining to specific research fields. In the first subproject of this program, entitled "Process and Procedures", which addresses questions on the procedural context, and specifically in the section "Organization, management, maintenance and recovery", we have singled out our theme.

[3] In the article 31 of this act, ordinary and extraordinary maintenance, restoration and recovery, building and urbanistic restructuration fall within the interventions aimed to the building rescue.
Throughout the text we made use of several words whose meaning is detailed as follows: rescue refers to the global process, whereas maintenance, restoration, recovery and restructuration refer to different types of the rescue.
Restoration and recovery interventions are those addressed to mantain the building organism and insure its functions trough a set of homogeneus actions that allow a compatible use respectable of its typological, formal and structural elements. Such interventions include strenghthening, restoration and renewal of the building constitutive elements, introduction of accessory elements and if required technological plants, removal of not related elements (Fourth Title, article 31, 457/1978 Act).

[4] Anamnesis: reminiscence. In medicine, a preliminary case history of medical patient, referable both to the investigation of the specific pathological condition and to general and foundamental stages of the patient's life, i.e., physiology, remote and recent pathology.

[5] Datum is any elementary information, generally rapresented by aggregates and classified as documents. For example, identification data of the building and of people who are legally bound to it, as well as evaluations made by the planner on the building preservation state, fall within this concept.

[6] Terminology used in the Card A, "Structure of Precatalogue Cards Data", by Central Institute for Catalog and Documentation, Italian Minister for Cultural and Environmental Affairs.

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Comparison of Vibration-Based Damage Assessment Techniques

Comparaison de techniques dynamiques de détection de dommages

Vergleich dynamischer Verfahren zur Schadenidentifikation

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SUMMARY
Three different vibration-based damage assessment techniques have been compared. One of the techniques uses the ratios between changes in experimentally and theoretically estimated natural frequencies, respectively, to locate a damage. The second technique relies on updating of a finite element method based on experimentally estimated natural frequencies where the stiffness matrix is given as a function of damage size and location. The last technique is based on neural networks trained with the relative changes in natural frequencies. It has been found that all techniques seem to be useful. The neural networks based technique seems to be very promising.

RÉSUMÉ
Trois techniques différentes de détection de dommage basées sur les vibrations sont comparées. Une des techniques utilise le rapport entre les fréquences propres mesurées expérimentalement et déterminées théoriquement. La seconde technique repose sur une mise à jour d'une méthode par éléments finis, basée sur des fréquences propres déterminées expérimentalement, et où la matrice de rigidité est donnée comme une fonction de la taille du dommage et de sa location. La dernière technique est basée sur des réseaux neuronaux entraînés par les changements relatifs dans les fréquences propres. L'article montre que les trois techniques sont opérationnelles. La technique basée sur les réseaux neuronaux semble très prometteuse.

ZUSAMMENFASSUNG
Drei verschiedene Techniken zur Schadenidentifikation werden verglichen, die alle auf Schwingungsmessungen beruhen. Ein Verfahren verwendet das Verhältnis der Aenderungen von theoretisch und experimentell bestimmten Eigenfrequenzen, um einen Schaden zu lokalisieren. Ein anderes beruht auf der Nachführung eines FE-Modells gemäss experimentell bestimmten Eigenfrequenzen, wobei die Steifigkeitsmatrix von Ort und Ausmass der Schädigung abhängt. Das dritte Verfahren benützt neuronale Netzwerke, die mit den relativen Aenderungen der Eigenfrequenzen trainiert werden. Insbesondere letztere Technik erscheint sehr vielversprechend.

1. INTRODUCTION

Determination of location and size of damages in civil engineering structures, damage assessment, using vibration measurements is a problem which has received much attention, recently, see e.g. Rytter [1]. Such vibration based inspection techniques are particular needed for dealing with large structures, such as civil engineering structures and large space structures, since they do not need assess to the structures for the investigator, such as those techniques based on e.g. visual inspection, ultrasonic testing, eddy currents and acoustic emission. Further, research in vibration based damage assessment techniques has been initiated by a considerable demand for a more accurate non-destructive damage assessment technique.

One of the consequences of a structural damage, such as a crack, is a change in local stiffness which in turn results in a decrease in some or in all the modal quantities, e.g. natural frequencies. The most commonly applied vibration based damage assessment techniques are based on changes of natural frequencies only. By comparing changes of experimentally measured modal quantities in structures with patterns of changes predicted theoretical implies that the location and/or size of the damage can be obtained. However, this requires knowledge of the theoretical changes of the modal quantities in the structure due to different locations and sizes of the damage. Therefore, the damage assessment results are depending on how well the mathematical model describes the dynamic behaviour of the damaged as well as the undamaged structure. The problem of establishing such models has been considered in e.g. Gudmundson [2], Ostachowicz et al. [3] and Okamura[4]. Based on such models one can estimated the changes in the dynamic behaviour due to a crack. However, damage assessment from measured changes in dynamic behaviour is the inverse problem, i.e. how can information be obtained about location and size of a damage given some experimentally measured modal quantities. Many techniques have been proposed to solve this inverse problem. A review of such techniques can be found in e.g. Rytter [1].

The aim of this paper is to investigate three different damage assessment techniques proposed to solve the inverse problem. These three different techniques are chosen since they represents three different damage assessment principles. One of the techniques uses the ratio of changes in experimentally and theoretically estimated natural frequencies, respectively, to locate a damage, see Cawley et al. [6]. The second technique relies on updating of an FEM where the stiffness matrix is given as a function of damage size and location, i.e. both location and size of the damage are estimated, see Shen et al. [7] and Rytter et al. [11]. The last technique is based on neural networks trained with the theoretically relative changes in natural frequencies as input and size and location of a crack as output, see Kirkegaard et al. [8].

Section 2 gives a description of the three different vibration based damage assessment techniques is given. In section 3 the described techniques are compared in an example with a straight hollow section steel cantilever beam. At last in section 4 conclusions are given.

2. DAMAGE ASSESSMENT TECHNIQUES

The following chapter presents the three different damage assessment techniques compared in this paper.

2.1 Cawley & Adams' Damage Detection Technique

In this section a damage assessment technique relying on the measurement of small changes in natural frequencies and upon adequate theoretical predictions of these frequency changes is presented. This technique can be used to give an estimate of the damage location. However, the technique does not give any indication of the quantity of the damage. The technique (briefly the CA-technique) is based on that fact that for small frequency changes the ratio of frequency changes in two modes is a function of the location of the damage only, see Cawley et al. [6]. Using an FEM to model a damage in a structure, theoretical values of the ratio of frequency changes in two modes can be obtained for various damage scenarios and modes. Observing the structure, both at virgin state and after a damage has been estasblihed the actual ratio of the frequency changes. Although some allowance must be made for inadequacy of the damage model used to estimate the theoretical frequency changes, the ratio of experimentally obtained frequency changes in two modes and the ratio of analytically obtained frequency changes in two modes, respectively, should have a close relation for the same damage scenarios and modes. In Cawley et al. [6] it is proposed to handle this matching problem by using an error e_{rij} quantity given by

$$e_{rij} = \frac{\frac{\Delta\omega^a_{ri}}{\Delta\omega^a_{rj}}}{\frac{\Delta\omega^m_i}{\Delta\omega^m_j}} - 1 \qquad \frac{\Delta\omega^a_{ri}}{\Delta\omega^a{}_{rj}} \geq \frac{\Delta\omega^m_i}{\Delta\omega^m_j} \tag{1}$$

$$e_{rij} = \frac{\frac{\Delta\omega^m_i}{\Delta\omega^m{}_j}}{\frac{\Delta\omega^a_{ri}}{\Delta\omega^a_{rj}}} - 1 \qquad \frac{\Delta\omega^a_{ri}}{\Delta\omega^a_{rj}} < \frac{\Delta\omega^m_i}{\Delta\omega^m_j} \tag{2}$$

where $\Delta\omega^a_{ri}$ and $\Delta\omega^m_i$ are analytically and experimentally obtained changes of the ith natural frequencies at location r, respectively.

Thus the total error e_r assuming the damage located at position r may be calculated as

$$e_r = \sum_{i=1}^{N_f}\sum_{j=1}^{N_f} e_{rij} \tag{3}$$

N_f is the number of measured modes. Normalising the total error e_r with respect to the minimum total error e_{min} implies a normalized error E_r given by

$$E_r = \frac{100 e_{min}}{e_r} \tag{4}$$

By this definition, the normalized error E_r will always be 100 for the position r which gives the smallest error e_{rij}.

One major disadvantage of the CA-technique is that the technique will locate a damage even if the natural frequencies have changed slightly, due to e.g. the temperature effects or the measurement noise.

2.2 Damage Assessment by Calibrating a FEM

In recent studies the damage assessment problem has been solved by a model updating procedure (briefly the UP-technique). A very used approach is to estimate the elements in the stiffness matrix for all the potential damage locations, see e.g. Smith et al. [9] and Richardson et al. [10]. The largest reduction in e.g. stiffness, compared with the stiffness of the undamaged structure, is giving the most likely damage location. These techniques belong to a general category of system identification techniques where parameters of an apriori analytical structural model such as its mass, stiffness, and damping are adjusted to minimize the difference between the analytically predicted and experimentally measured dynamic characteristics. If the stiffness matrix is given as a function of damage size and location it is also possible to estimate the magnitude of the damage, see e.g. Shen et al. [7] and Rytter et al. [11].

This implies that the following optimization problem can be formulated, see Rytter et al. [19]

$$\min_{r,a} \quad log\left(\sum_{i=1}^{N_f}\left(\frac{\frac{\omega_i^{mp}}{\omega_i^{mv}}}{\frac{\omega_{ri}^{ap}}{\omega_{ri}^{av}}} - 1\right)^2 W_i\right) \tag{5}$$

$$s.t \quad \left|\frac{\omega_{ri}^{ap}}{\omega_{ri}^{av}} - \frac{\omega_i^{mp}}{\omega_i^{mv}}\right| \leq \beta_i \tag{6}$$

where ω_{ri}^{ap} and ω_i^{mp} are analytically and experimentally obtained values for the damaged structure (periodical measurement), of the ith natural frequency, respectively. ω_{ri}^{av} and ω_i^{mv} are analytically and experimentally obtained values, for the undamaged structure (virgin state measurement), of the ith natural frequency, respectively. W_i and β_i are weighting parameters established from the accuracy of the estimates of the natural frequencies. In Rytter [1] it is shown that the formulation of the optimization problem (6) is important in order to avoid or reduce the problem of local minima.

2.3 Damage Assessment by using Neural Networks

Above it is explained how the damage assessment problem can be solved using optimization. Such a procedure based on minimization of a measure of the difference between measured data and the corresponding predictions obtained from a mathematical model implies a comprehensive search which is computationally expensive and nearly impossible for complex structures. Therefore, a pattern recognition scheme could be needed to decipher the complex pattern of dynamic behaviour changes that occurs due to a damage. However, recently, artificial neural networks are proving to be an effective tool for pattern recognition in a variety of applications, see e.g. Hertz et al. [12] and among these also for damage assessment. In Kirkegaard et al. [8] a neural network (briefly the NN-technique) has been trained with the relative changes in natural frequencies obtained by an FEM. The network is then used to estimate location and size of a crack in a beam from measured natural frequencies.

2.3.1 Neural Networks

Many different types of neural networks have been proposed by changing the network topology. Examples of those are e.g. the Hopfield network, Hopfield [13], the Kohonen network, Kohonen [14] and the so-called multilayered perceptron (MLP) network. The MLP trained by the back-propagation algorithm is currently given the greatest attention by application developers, see e.g. Hertz [12]. The MLP network belongs to the class of layered feed-forward nets with supervised learning. A multilayered neural network is made up of one or more hidden layers placed between the input and output layers, see fig. 1.

Each layer consists of a number of nodes connected in the structure of a layered network. The typical architecture is fully interconnected, i.e. each node in a lower level is connected to every node in the higher level. Output units cannot receive signals directly from the input layer. During the training phase activation flows are only allowed in one direction, a feed-forward process, from the input layer to the output layer through the hidden layers. The input vector feeds each of the first layer nodes, the outputs of this layer feed into each of the second layer nodes and so on. Associated with each connection between node i and node j in the preceding layer $l-1$ and following layer l is a numerical value $w_{lj,i}$ which is the strength or the weight of the connection.

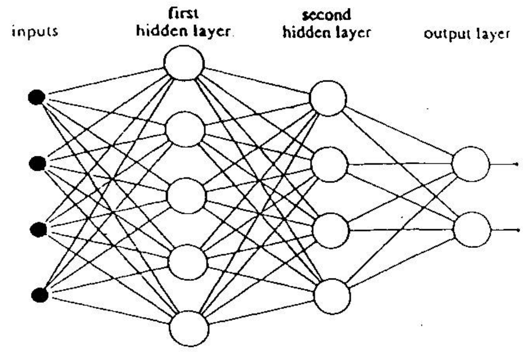

Fig. 1: Principle of a multilayer perceptron neural network.

At the start of the training process these weights are initialised by random values. Signal pass through the network and the jth node in layer l computes its output according to

$$x_{lj} = f(\sum_{i=1}^{N_{l-1}} w_{lj,i}x_{l-1,i} + \theta_{lj}) \tag{7}$$

for $j = 1,..,N_l$ and $l = 1,..,k$, where x_{lj} is the output of the jth node in the lth layer. θ_{lj} is a bias term or a threshold of the jth neuron in the lth layer. The kth layer is the output layer and the input layer must be labelled as layer zero. Thus N_0 and N_k refer to the numbers of network inputs and outputs, respectively. The function $f(\cdot)$ is called the node activation function and is assumed to be differentiable and to have a strictly positive first derivative. For the nodes in the hidden layers, the activation function is often chosen to be a so-called sigmoidal function

$$f(\beta) = \frac{1}{1+e^{-\beta}} \tag{8}$$

The activation function for the nodes in the input and output layers is often chosen as linear.

The first stage of creating an artificial neural network to model an input-output system is to establish the appropriate values of the connection weights $w_{lj,i}$ and thresholds $\theta_{lj}$by using a learning algorithm. A learning algorithm is a systematic procedure for adjusting the weights in the network to achieve a desired input/output relationship, i.e. supervised learning. The most popular and successful learning algorithm used to train multilayer neural networks is currently the Back-propagation routine, see Rumelhart [15]. The so-called Back-propagation algorithm employs a gradient descent search technique for minimizing an error normally defined as the mean square difference between desired and actual outputs from the network.

During the training phase, representative examples of input-output patterns are presented to the network. Each presentation is followed by small adjustments of weights and thresholds if the computed output is not correct. If there is any systematical relationship between input and output and the training examples are representative of this, and if the network topology is properly chosen, then the trained network will often be able to generalise beyond learned examples. Generalisation is a measure of how well the network performs on the actual problem once training is complete. It is usually tested by evaluating the performance of the network on new data outside the training set. Generalisation is most heavily influenced by three parameters: the number of data samples, the complexity of the underlying problem and the network architecture. Currently, there are no reliable rules for determining the capacity of a feed-forward multilayer neural network. Generally, the capacity of a neural network is a function of the number of hidden layers, the number of processing units in each layer, and the pattern of connectivity between layers. However, it is shown in Cybenko [16] and Funahshi [17] that one hidden layer is sufficient to approximate all continuous functions. The process of computing the gradient and adjusting the weights and thresholds is repeated until a minimum of the error is found. However, it is generally true that the convergence of the Back-propagation algorithm is fairly slow. Attempts to speed learning include variations on simple gradient search, line search techniques and second order techniques, see e.g. Hertz [12] and Billings [18].

2.3.2 Use of Neural Networks for Damage Assessment

When an artificial neural network is used for damage assessment the basic idea is to train the neural network in order to recognise the behaviour of the damaged as well as the undamaged structure. Subjecting this trained neural network to information from vibration tests should imply information about damage state and location. The network is trained with patterns of the changes in quantities describing the dynamic behaviour that occur due to a damage. This implies that each pattern represents the computed changes of e.g. the response spectrum, natural frequencies, mode shapes etc. due to a damage of a particular size at a particular location. The patterns of the quantities describing the dynamic behaviour are used as inputs and the damage location and size as outputs to train the neural network. Then the trained network subjected to measured patterns of the quantities describing the dynamic behaviour can be used to determine the location, size and of a damage. The training of a neural network with appropriate data containing the information about the cause and effect is a key requirement of a neural based damage assessment technique. This means that the first step is to establish the training sets which can be used to train a network in a way that the network can recognise the behaviour of the damaged as well as the undamaged structure from measured quantities. Therefore, ideally, the training sets should contain data of the undamaged as well as the damaged structure in various damage states. These data can be obtained by measurements, model tests or through numerical simulation, or through a combination of all three types of data. This possibility of using all obtained information, or only a part, in a neural network based damage assessment technique is a capability which is not available in traditional damage assessment techniques.

3. EXAMPLE

In this example the three different damage assessment techniques are applied to a hollow section steel cantilever, see fig 2.

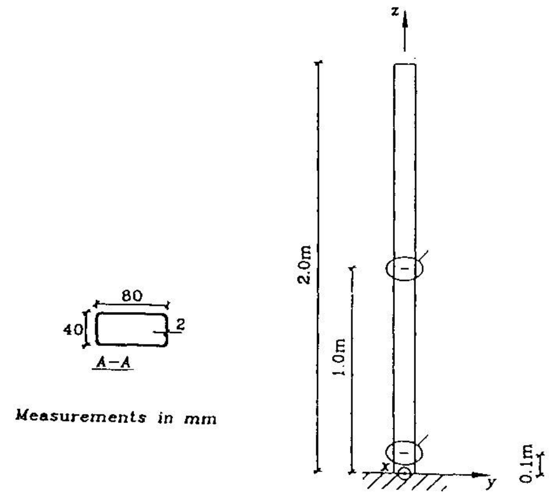

Fig. 2: Test structure.

3.1 Analytical and Experimental Results

The experimental data used in this example are estimates of the lowest three bending natural frequencies. Real line cracks were obtained in the test beams by attaching a sinus-varying load to the beams by means of a shaker. The frequency of the sinus was either the actual first or second bending natural frequency. The cracks lengths were measured by means of a microscope mounted on an electrical measurement rail. Two different crack locations were considered. In one beam a crack was initiated at z=1.0 m and in an other beam at z=0.1 m. The cracks were initiated as small narrow laser cuts (width ≈ 0.15 mm). The experimental determination of the bending natural frequencies was obtained from free decays. The free decays were introduced by removing a well-defined static load from the beam momentary. The accelerations were measured at z=0.5 m, z = 1.4 and z=2.0 m. The natural frequencies were estimated by a minimization of the least square error between the response obtained by an analytical expression of a linear and viscously damped system and the measured response. A more throughout description of the experimental procedure and the experimental results can be found in Rytter et al. [1].

The analytical estimated changes of the natural frequencies are estimated by an FEM of the beam. The development of a crack at a certain location of a beam corresponds to a sudden reduction of its bending stiffness at the same location. The crack divides the original non-cracked beam into two shorter beams, connected, at the crack location, by a very infinitesimal portion of beam with different characteristics. The characteristics in bending modes can be modelled by a torsion spring. The spring stiffness is estimated by using a fracture mechanical model, see e.g. Okamura[4] and Gomes et al. [5]. The FEM was calibrated by using experimental data from the non-cracked beam. This calibration was performed to secure that the FEM describes the beam in the best possible way. The quality of the predictions from any technique of damage assessment is critically dependent on the accuracy of the damage model, see e.g. Rytter [1].

3.2 Results

In the following it is explained how the three different damage assessment techniques were implemented in order to detect and locate the cracks in the beams.

3.2.1 The CA-Technique

In order to use the CA-technique the errors given by (4) were calculated using analytical and experimental values of the three lowest natural frequencies. The analytical values were estimated due to a crack of 0.06m placed in intervals of 0.025 m between $z = 0.0m$ and $z = 2.0m$. The crack locations estimated using the CA-technique are shown in fig. 3 with a dotted line.

3.2.2 The UP-Technique

The applicability of the UP-technique was tested by solving the optimization problem formulated in (5)-(6). Again the three lowest natural frequencies were used. This means that the optimization variables were size a and location z of the crack. The initial value of a and z were taken as 0m and 1.5 m, respectively. The crack locations and sizes estimated using the UP-technique are shown in figure 3 and 4, respectively with a dashed line.

3.3.3 The NN-Technique

The neural network results were obtained using a hierarchical, two step approach. This implies that the relative changes of the bending natural frequencies of the 3 lowest modes and the location of the crack are used as input and output, respectively, in one network. In an other network the crack location and the relative change of the bending natural frequencies of the 3 lowest modes are used as inputs and the size of the crack as output. A hierarchical approach was used since it was found in Kirkegaard et al. [8] that better results could be obtained instead of using only one big network. The training sets were generated for cracks located in intervals of 0.025 m between z = 0 m and z = 2.0 m, respectively. The cracks depths were in intervals of 0.004 m between 0.02 m and 0.140 m. By a trial-and-error approach it was found for the first network that a 4 layers neural network with 3 input nodes, 8 nodes in each of the two hidden layers and 1 output node gave the network with the smallest output error. For the second network it was found that a 4 layers neural network with 4 input nodes, 8 nodes in each of the two hidden layers and 1 output node gave the smallest output error. Results from the networks trained with analytical data and subjected to experimental data are shown with a dashed-dotted line in figure 3 and 4, respectively.

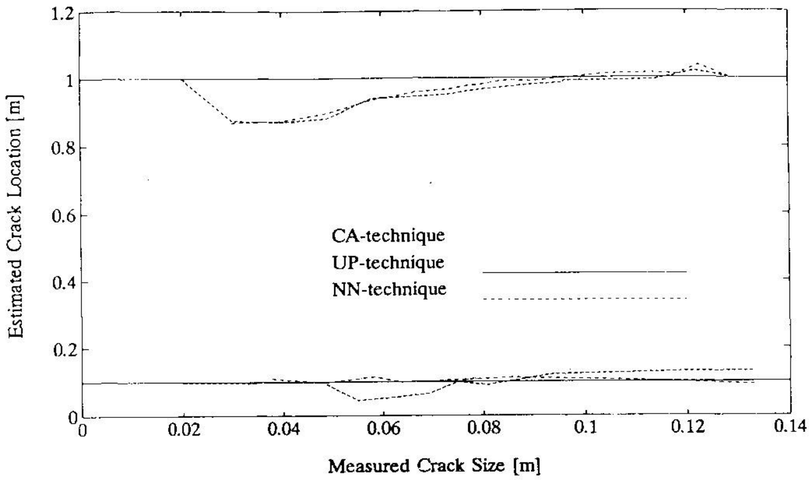

Fig. 3: Estimated crack location.

It is seen from figure 3 an 4 that the estimated location and size of the two cracks obtained by the three techniques are reasonably correct for all crack sizes. Especially, the estimates obtained by the NN-technique are interesting. By using the NN-technique the location and size of the crack can be estimated on-line. Figure 3 also shows that the influence from errors on the measured natural frequencies becomes smaller for increasing crack length.

4. CONCLUSIONS

Results from an example with a hollow section steel cantilever demonstrate the capability of three different vibration based damage assessment techniques. The techniques rely on the measurements of small changes in natural frequencies and upon adequate theoretical prediction of these frequency changes. It is explained how the damage assessment problem can be solved using optimization. It is found that the size and location of cracks can be predicted using the three techniques. Especially, the estimates obtained by a neural network based technique seems to be encouraging. By using the neural network based damage assessment technique an on-line technique is established. In the following work the neural based technique for detecting and locating damages in civil engineering structures based on vibration measurements has to be investigated.

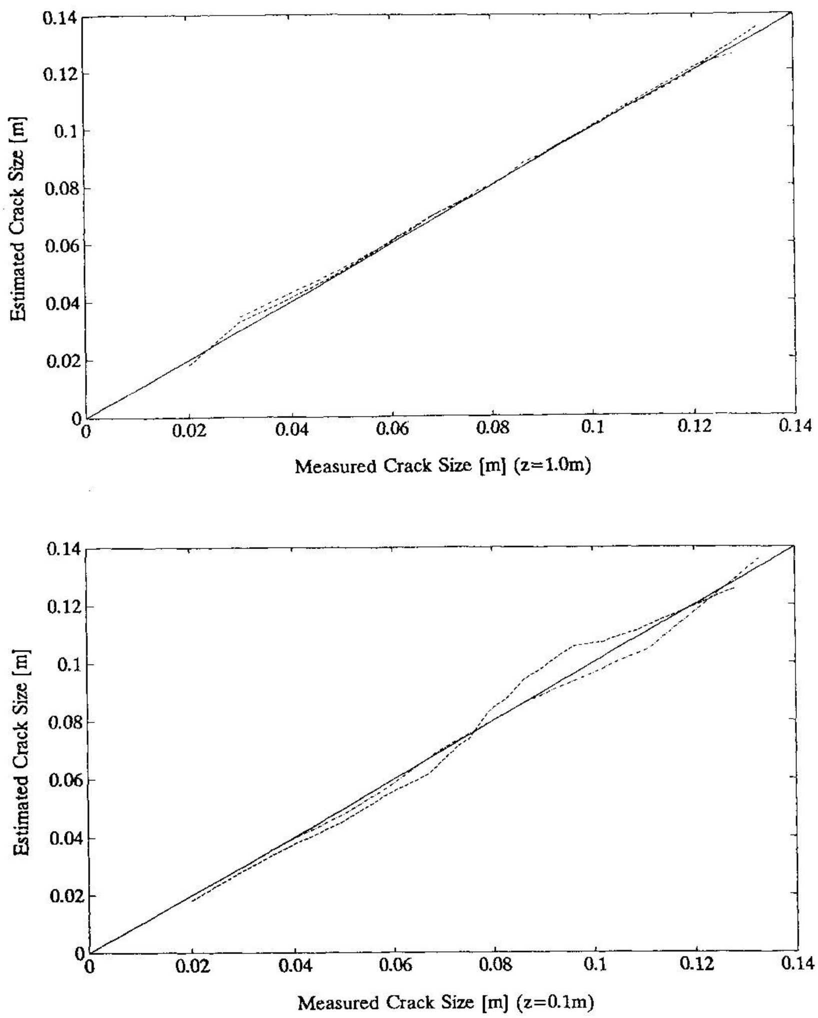

Fig. 4: Estimated crack size.

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Diagnostic Reasoning in Monitoring of Civil Engineering Structures

Exploitation des données pour la surveillance des ouvrages d'art

Diagnostische Datenauswertung in der Bauwerksüberwachung

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SUMMARY
The paths of diagnostic reasoning implemented in two in-service real-time systems for monitoring the structural safety of monuments and dams are presented. They are based on multiple representations of the physical system through multiple state spaces. Each state space include possible, desirable and undesirable states. Various paths of reasoning may be used through different spaces. The use of multiple spaces and paths allows to exploit the available information and to accumulate evidence on the safety of the structure. These types of reasoning are typical in monitoring of civil engineering systems because they help to manage the fundamental problem of incomplete knowledge.

RÉSUMÉ
L'article présente les cheminements utilisés dans deux systèmes de surveillance, en temps réel, de la sécurité structurale des monuments et barrages. Ils sont basés sur des représentations du système physique dans l'espace et dans le temps. Des situations possibles, désirables et indésirables sont considérées. Les cheminements varient selon les espaces. Il est possible d'exploiter l'information disponible et d'évaluer la sécurité de la structure. Ce genre de raisonnement est typique dans la surveillance de systèmes en génie civil car il pallie la connaissance toujours incomplète.

ZUSAMMENFASSUNG
Es werden die Pfade für die diagnostische Datenauswertung vorgestellt, wie sie in zwei Echtzeitmesssystemen zur Ueberwachung der Standsicherheit historischer Bauwerke und Staumauern implementiert sind. Sie basieren auf Repräsentationen des physikalischen Systems in mehrfachen Zustandsräumen, die jeder mögliche, erstrebenswerte und nicht erstrebenswerte Zustände beinhalten. Dank mehrfacher Räume und Pfade können aus unvollständigen Informationen Anhaltswerte für die Standsicherheit eines Bauwerkes zusammengetragen werden.

1. INTRODUCTION

Monitoring is an important activity related to the management of structures in service. Networks of sensors and data acquisition systems allow engineers to collect data from structures such as dams or monuments. Engineers interpret data by mapping them into states and behaviours of structures and evaluate those states against some reference model to decide actions. They use various types of knowledge and follow paths of reasoning through these types of knowledge.

In the following the reasoning paths common to two A.I. applications to structural monitoring are presented. The first system (KALEIDOS) supports the real-time interpretation of a net of 120 sensors installed on the Cathedral and six medieval towers of Pavia. It is operational from February 1994 [3]. The second system (MISTRAL) helps with managing the safety of an arch-gravity dam. The system interprets data coming from 40 sensors and is operational from mid 1992 [4]. A second instance of the system is going to be installed on an other arch-gravity dam.

The reasoning paths of the two systems are defined in the context of a common conceptual framework which is based on multiple descriptions of the monitored structure using multiple state spaces.

Various reasoning paths are used inside a state space representation or between different state spaces. Each reasoning path contributes to the evaluation of the safety of the structure. We argue that these types of reasoning are typical for this kind of problems. The main reason is that they are related to the management of incomplete knowledge, which is a fundamental problem of the diagnosis of civil engineering systems.

2. REASONING PATHS

An expert engineer is able to use different types of knowledge, such as empirical associations and causal models, compiled knowledge, qualitative and quantitative models and hierarchical descriptions. He is also able to organise and use the above mentioned knowledge through reasoning processes related to the specific tasks to be performed.

A model of this kind of expertise is presented in [5]; different layers of knowledge are described:

① *domain level*;

② *inference level*;

③ *task and strategic level*.

The *domain level* contains concepts, relations among concepts, models of processes or devices.

The *inference layer* describes which inferences can be made on the basis of the previous level. Examples of possible inferences may be:

Abstract (deletes attributes from a concept)

Match (compares structures of concepts)

Different inferences may be linked together in different ways, according to specific tasks (*task and strategic level*). This generates different paths of reasoning. An example of a path may be:

data → (abstraction) → evidence → (association) → diagnosis

3. STATE SPACES

Different reasoning paths may be used to solve interpretative problems. In the following we will relate all these reasoning paths to a common system view.

In this view the state space of a system is the set of possible (and not possible) states of the physical system. Moreover the state space includes, within the area of possible states, two sets defining desirable and undesirable states.

Note that the set of possible states is not the union of the desirable and undesirable states. The reason is that, while (im)possible states express the semantics of the model, (un)desirable states express the pragmatics (we want that the system behaves as near as possible to the desirable states and as far as possible from the undesirable ones). This is a common way to try to control systems which are not completely known (i.e. the system may reach not optimum states or not well known states but has not to reach critical states). Based on the space state, different tasks are possible:

- identify, using the available information, the current state of the physical system in the space state;
- compare the current state with the desirable ones to evaluate the distance between the current state and the border of the desirable states area;
- predict the evolution of the current state (identify one or more paths starting from the current state);
- explain the reason of the current state in term of the past evolution of the state (identify one or more paths to the current state);
- compare the current state with the not desirable ones and evaluate the distance between the current state and them;
- predict possible evolution of the current state, due to particular external events (e.g. earthquakes or floods) to evaluate if the system state could reach some undesirable state.

The same physical system may be described by many different state spaces. For instance, a first space may by defined using a data model: possible states are defined through possible values of a set of variables; the current state is described by the current set of values, while desirable and undesirable states are defined through thresholds derived from past observations.

A second state space may use a statistical model derived from past observations or a model of the design behaviour of the structure: possible states are defined through possible values of input and output variables of the model; the relationship identified by the model defines desirable states while thresholds define undesirable states.

A third state space may use a causal net of possible physical processes [2]; possible states are possible activation states of the processes, while desirable or undesirable states are specific activation states.

The reasoning in interpretative tasks is a path through a state space or through many state spaces described by different models and data. Different paths are possible depending on the specific goal, the available knowledge and the existing constraints.

4. PATHS OF REASONING IN MONITORING OF CIVIL ENGINEERING STRUCTURES

Typical paths of reasoning in monitoring of civil engineering systems are described in the following. These reasoning paths are used by two in-service systems (KALEIDOS for monitoring of monuments and MISTRAL for monitoring of dams) which will be shortly presented in the next chapters.

4.1. Reasoning about single measurements (RP1)

The state space is identified by effect variables (e.g. displacements of dam blocks are effect variables, while level of basin and air temperature are cause variables) which are measured by the monitoring system. Each variable has real values and is considered separately.

Desirable and undesirable states are defined through thresholds. Each variable has a set of thresholds which are derived from past history. They split the possible states into subspaces (from normal to highly anomalous).

The reasoning path is as follows: each measured value is filtered, then the result is compared with the relevant thresholds and the location of the current state in the subspaces (normal, low anomaly, medium anomaly, high anomaly, very high anomaly) is identified.

Moreover, not only the original measurements may be processed in such a way, but also their derivatives. The reasoning path is described in the following graph:

data	→	(filtering)	→	current state	→	(comparison with thresholds)	→	desirable / undesirable state
[data space]				[single measurements space]				[single measurements space]

According to [5] the *domain level* contains the following concepts: *data, states of the type "single measurements"* (classified in current, desirable and undesirable) and *thresholds*; the *inference layer* contains *filtering* and *comparison with thresholds*; the *task level* links domain concepts and inferences generating the above written reasoning path.

4.2. Reasoning about cause-effect measurements groups and associated models (RP2)

Groups of causes and related effect variables are considered. For each group (a set of causes and one effect) desirable and undesirable states are defined using quantitative models and thresholds. The models may be derived from past observations or from the design behaviour of the structure. For instance, a model may describe the relationship between water level of the basin and air temperature (causes) and displacement of a point of a dam block (effect).

For each group all the measurements are filtered, then the model is used to compute the effect from the measured causes. Then the measured effect is compared with the computed one. Possible situations may be

- the value of the measured effect variable is outside thresholds defining in any case an anomalous state;
- the value of the measured effect variable complies with the computed one (considering a possible range of variations defined by thresholds) and is not outside the above mentioned thresholds defining anomalous states. The state is normal;
- the value of the measured effect variable does not comply with the computed one, nor is outside the above mentioned threshold defining anomalous states. In this case the model and the measurements are inconsistent. This is usually regarded as a dangerous situation

(something is happening which we are not able to explain). The state is considered anomalous.

The reasoning path is described in the following graph:

data	→	(filtering & grouping)	→	current state	→	(computation of effects & comparison through models & thresholds)	→	desirable / undesirable state
[data space]				[causes / effect groups space]				[causes / effect groups space]

4.3. Reasoning about families of measurements (phenomena) (RP3)

The state space is identified by sets of effect variables belonging to the same type of instruments (e.g. the set of extensometers installed on a dam).

Each set identifies a global behaviour of the physical system which we call *phenomenon*. The identification of a phenomenon means that we are not able to identify a particular physical process in the structure (e.g. a highly anomalous rotation of a dam block). Nevertheless we may identify a more general and uncertain situation (e.g. highly anomalous movements of the structure). In some cases the available information could be not sufficient to identify a particular process, but the general behaviour of a family of instruments may provide sufficient evidence for an abnormal situation.

The desirable and undesirable states are defined though sets of empirical rules which take into account the significance and the reliability of each instrument. The values of each set of variables are filtered and then interpreted as possible evidences for a particular state (from normal to highly anomalous) and the rules are applied to find if sufficient evidence for a particular state holds. The reasoning path is described in the following graph:

data	→	(filtering & grouping)	→	current state	→	(association through empirical rules)	→	desirable / undesirable state
[data space]				[phenomena]				[phenomena]

4.4. Reasoning about processes (RP4)

The state space is identified by a set of possible physical processes which may be active in the structure (e.g. rotation, translation, seepage).

Each process has a state, from a desirable one (normal) to a highly undesirable (very high anomaly). This state is defined through qualitative models expressing relations among effect variables. The models describe physical or geometrical constraints among measurements. The values of the variables are abstracted from real values to qualitative descriptions (e.g. the rotation process of a dam block may be not active, low, medium, high, very high. A high downstream displacement of a plumbline installed on the block and a high compression of a strain gauge in foundations under the block imply a high downstream rotation process of the dam block).

The reasoning path is as follows. The measured quantities are abstracted from real numbers to a suitable quantity space. Then, for each possible process, the associated qualitative model, which is used as a set of constraints, is applied. If some constraint is true, the relevant process status is asserted.

Note that in some cases also quantitative models are used, but their meaning is different than in RP1. In RP1 a model is a relationship between causes and effects which is used to compute the latter, given the former. In RP4 models are constraints among effect variables which may be used to verify the existence of evidences for a possible physical process. The reasoning path is described in the following graph:

data	→	(qualitative abstraction)	→	qualitative data	→	(verification of constraints)	→	desirable / undesirable state
[data space]				[qualitative data space]				[processes space]

4.5. The integration of different reasoning paths

Monitoring systems such as KALEIDOS or MISTRAL use more than one reasoning path. An obvious problem arises: how to integrate different paths and the different interpretations they provide?

A first consideration is that all the measurements, models, phenomena or processes are referred to a common physical structure which may be split in parts (e.g. a dam system may be composed of dam blocks, basin, foundation).

The interpretation system maintains an object-based description of the physical system and every attribute or reasoning is referred to a specific object (e.g. the whole dam or a block of the dam).

Nevertheless, different reasoning paths are used together because the knowledge of the physical system behaviour is incomplete. For each object composing the system as well as for the whole system itself, different paths may be applied. Each of them provides a state which may be interpreted as evidence for the global state of the object.

Influence rules are used to describe the contribution of each state to the global one. These rules are used to summarise, through a conservative approach, the interpretation results for warning purposes. Moreover, the whole available interpretation results coming from the different reasoning paths are presented and explained to the user, because each of them may be used to support a human decision providing different types of evidences for the evaluation of the safety of the structure.

5. FIRST APPLICATION: MONITORING OF MONUMENTS

An application of the previously presented paths of reasoning is the KALEIDOS system which has been developed for the on-line management and interpretation of the measurements gathered on monuments. The first version of the system was delivered for the management of the safety of the Cathedral of Pavia and of six towers in the same town.

On March 17, 1989 the Civic Tower of Pavia collapsed. After this event, the Italian Department of Civil Defence appointed a technical-scientific committee to analyse the causes of the collapse and to check the state of other monumental structures of the town. The work of the Committee included a plan of monitoring surveys and interventions to be carried out on the Cathedral of Pavia and on six towers. This plan led to the installation by ISMES, in 1990, of an automatic monitoring system linked via radio to a control centre, located at the University of Pavia.

The instrumentation (120 sensors) installed on the Cathedral and on the towers allows to acquire the most important measurements on each monument, such as opening/closure of significant cracks, displacements, stresses and also cause variables, such as air temperature, solar radiation, groundwater level and so on.

The data gathered on the monuments are checked by the monitoring system to evaluate the reliability of the measures and to highlight any anomaly. Then, the data are periodically transferred into the historical data base MIDAS, which allows the off-line analysis, post-processing and plotting of data.

In such situation, two kinds of risk were identified, which suggested the development of an *intelligent* system for the monitoring of the structures.

First of all, the monitoring systems currently available allow the carrying out of checks on single values gathered by each instrument. Therefore, these checks neither deal with more than one instrument at a time, nor with more than one reading at a time for each instrument. In addition, any behaviour (either of the structure, or of the instruments) which is not consistent with the reference model generates a warning message. Because of the limited interpretation skills of the people on-site, false alarms cannot be identified and therefore require expert attention.

On the other hand, off-line expert analysis on series of data may require delays not compatible with the needs of the safety management of the structures.

The use of artificial intelligence techniques allowed to improve the capabilities of the monitoring system. AI contributed in collecting the expert knowledge related to data interpretation and delivering it through a system linked with the existing monitoring system. The system, called KALEIDOS (Fig 1), can filter and classify the anomalies by using different types of knowledge (e.g. geometrical and physical relationships). It can take into account the whole set of measurements and warnings to identify the state of the monitored structures and to explain it. This allows a part of the expert interpretation to be performed on-line, and therefore to *reduce* the requests for expert intervention and to *increase* the level of safety of the structures.

KALEIDOS is comprised of the following modules:

- *communication module*: manages the data transfer from the monitoring system;
- *evaluation module*: identifies the state of the structure;
- *explanation module*: generates natural-language explanations of the deductions of the evaluator;
- *man/machine interface*: allows the user to go through the results of the computation;
- *database management module*: manages a database of measurements and evaluations.

The communication module calls the monitoring system and receives the data gathered during the last acquisition (normal real-time procedure) or collected while KALEIDOS was, for some reason, not active.

The *evaluator* interprets the data, using different state space representations and reasoning paths and provides the safety status of the structures. From the trace of execution, using knowledge about the behaviour of the structure and the instruments, the *explanation module* generates natural language messages. They describe the current state of the structure and the deductions of the system.

The user can go through the results of the processing through a *window-based interface*. The interface draws on the screen graphical representations of the objects which have been assessed (instruments, towers, columns, ...) and displays them using a colour scale based on the state of the object. Interactors are available to get more refined information about the state of the structures, by focusing on interesting details.

KALEIDOS provides the users with a *static data base* of test cases, and a *dynamic database* collecting all the data related to the control system (measurements, evaluations, explanations). It is possible to select a situation from the data base and show on the screen its graphic representation and explanations.

KALEIDOS was developed and delivered on personal computers using Prolog, C and VisualBasic under MS Windows.

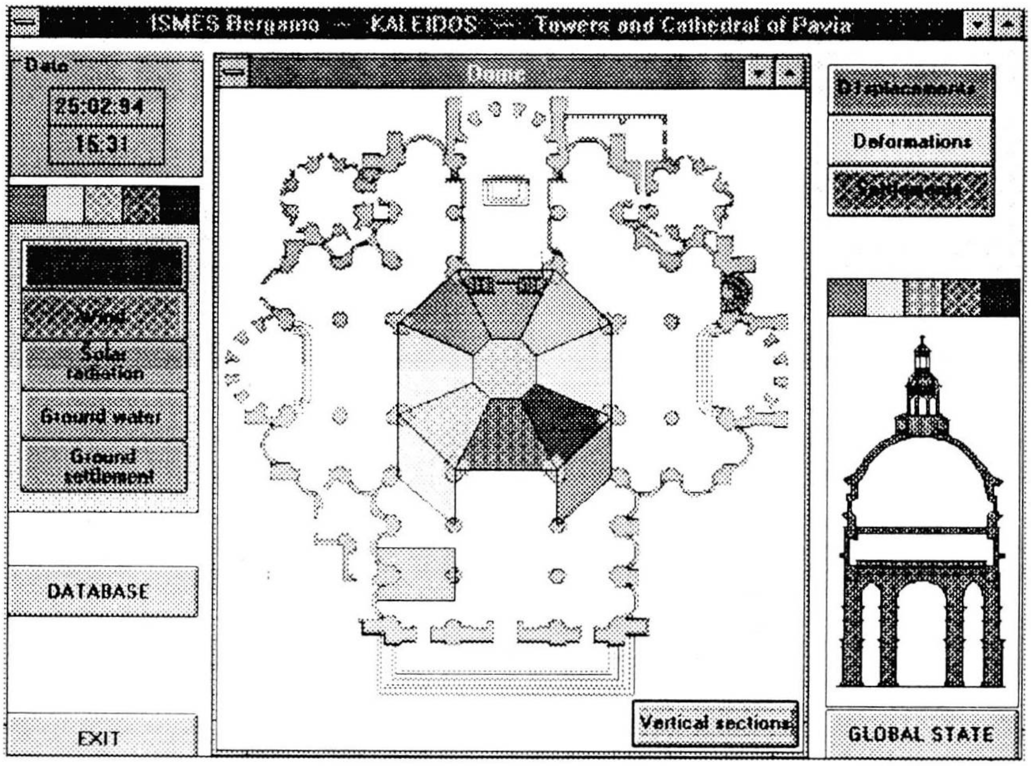

Fig 1. The KALEIDOS system

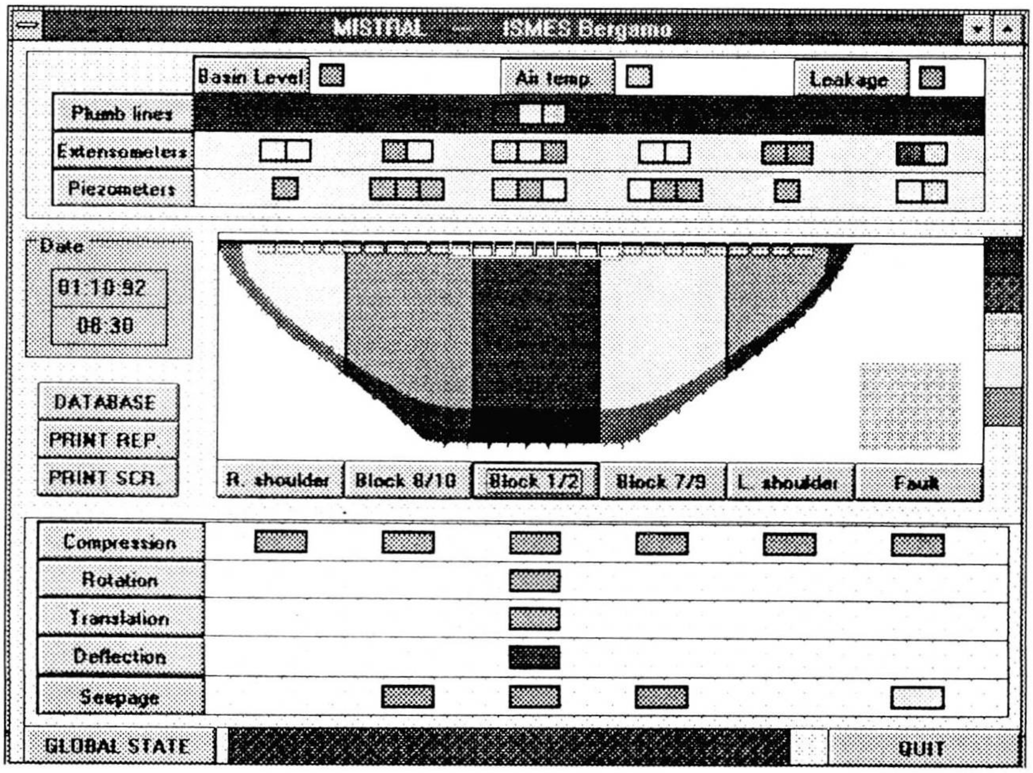

Fig 2. The MISTRAL system

6. SECOND APPLICATION: MONITORING OF DAMS

A second application is the MISTRAL system, which is a real-time system for the interpretation of data acquired from monitoring of dams. It shares the same architecture and technology of KALEIDOS. More detailed information may be found in [4].

Fig 2 shows how the information resulting from the execution of the reasoning paths is presented to the user. Small square lights on the top of the screen codify, on a colour scale ranging from green to red, the state of the instruments as defined by the reasoning paths RP1 and RP2. These squares lie on coloured strips, whose colours represent the state of the phenomena processed in the reasoning path RP3. Rectangular lights in the lower part of the screen codify the activation state of the processes, as detected in the reasoning path RP4. The colours of the blocks of the dam and of the strip on the bottom of the screen summarise the state of the structural components of the physical system and of the whole structure.

7. CONCLUSIONS

Previous chapters describe the diagnostic reasoning implemented in two applications of Artificial Intelligence technologies to the diagnosis of civil engineering systems.

Interpretative problems related to civil engineering structures have specific characteristics due to the types of systems they deal with. In the following, some specific aspects are listed:

1. a large engineering facility, such as a dam or a marine structure, is situated in a natural environment. The definition of the borders of the system may not be clear and depends on the goals of the interpretation problem;
2. the system is usually made of a limited number of components (on the contrary other engineering artefacts such as electronic circuits may have a very large number of components);
3. the system behaves as a continuum and is usually difficult to distinguish individual components with well defined interactions;
4. each component is known with uncertainty (e.g. the behaviour of materials is not well understood);
5. engineering facilities interact with the social environment both for operation and use of them;
6. in many cases civil engineering systems (e.g. dams) are one-off products (i.e. there is not a large population of similar artefacts which may be studied with statistical techniques as in the manufacturing industry);
7. structures are subject to uncontrolled and, to some extent, unpredictable input (for example earthquakes and floods). Moreover, it is difficult, if not impossible, to test them at full scale against design load conditions in order to verify models;
8. the characteristics of the available knowledge may be highly influenced not only by technical issues but also by economical ones. For instance, the evaluation of the possible seismic damage of an urban nucleus needs to be accurately planned to balance the cost of the information and the value of the predictions which can be drawn from the available data.

The decisions in interpretative problems are based on modelling and reasoning with models of physical systems. Models of different types may be used: associational, causal, qualitative, quantitative and so on.

Each model describes some specific aspect of the physical system and is built or selected for a specific goal. In this sense, knowledge is in any case incomplete. Nevertheless for many situations it is possible to define the purpose and the scope of the model and then reasonably depend on the results of the model itself by assuming that it describes a complete view of a specific aspect of a physical system. This assumption is difficult in many practical interpretative problems of civil engineering systems. Engineers deal with *open world models* [1]; in this kind of models there is only partial knowledge about a system and a situation where everything is true or false does not hold. Some things are true, some false, some unknown and some are inconsistent.

Decisions are required even if the available knowledge is incomplete. Therefore the management of incomplete knowledge and the use, in a co-ordinated manner, of every type of knowledge (e.g. empirical knowledge as well as causal, qualitative or quantitative models) is a fundamental issue.

The approach above presented is based on the following aspects:

- multiple representations of the physical system;
- use of various reasoning paths through which many different types of available knowledge are used to exploit the available information and increase the evidences about the status of the structure.

These aspects are means to manage the fundamental issue of incomplete knowledge in monitoring of civil engineering systems; therefore, we think that the approach experimented in the two in-service systems above described may be widely applicable.

Finally we think that the definition of the state spaces conceptual structure and of the reasoning paths is an important issue at least for the following reasons:

- it provides a way to understand and model the expertise of engineers;
- it increases the ability to design, compare and communicate the A.I. based monitoring systems, because it provides an abstract way to model the system which is independent from the implementation.

ACKNOWLEDGEMENTS

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New Approach toward Bridge Management Database Systems

Nouvelle approche pour les systèmes de base de données des ponts

Ein neuer Ansatz für Brückendatenbankmanagementsysteme

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SUMMARY

Conventional bridge management database systems have many limitations in expressing bridge components, historical and geographical data of the bridge environment, and in integrating image information. A prototype bridge database system using new information technology is proposed to overcome these limitations. An object-oriented Geographic Information System database, and image and video processing are introduced to the bridge management database system. These improvements make it possible to use the system during the whole life cycle of the bridge, from the planning stage to the maintenance stage.

RÉSUMÉ

Les systèmes conventionnels de bases de données pour la maintenance des ponts sont limités quant à la description des éléments des ponts, leur histoire, leurs données géographiques de l'environnement du pont, de même qu'à l'intégration de l'information des images. Une base de données utilisant de nouvelles technologies informatiques est proposée pour surmonter ces obstacles. Un système d'information géographique, à base de données orientée-objet, et un traitement des images par la vidéo sont introduites dans le système. Les améliorations devraient permettre l'utilisation du système proposé pendant tout le cycle de la vie des ponts, de la conception à l'exploitation.

ZUSAMMENFASSUNG

Konventionelle Brückendatenbankmanagementsysteme sind sehr beschränkt bezüglich der Erläuterung des Brückenaufbaus, den historischen Daten sowie der geographischen Daten der Brückenumgebung. Es wird ein Prototyp eines Brückendatenbanksystems vorgeschlagen, der eine neue Informationstechnologie verwendet, um diese Einschränkungen zu überwinden. Ein geographisches Informationssystem, eine objektorientierte Datenbank sowie Bild- und Videoverarbeitung werden in das Brückendatenbankmanagementsystem eingeführt. Aufgrund dieser Verbesserungen sollte es möglich sein, dieses System während des gesamten Lebenszeitraums der Brücke, vom Planungsstadium bis hin zur Instandhaltung, zu verwenden.

1. INTRODUCTION

Because of the lack of maintenance of the infrastructures in the U.S.A., these structures are undergoing rapid deterioration. This is specially true for bridges where 20% of the total number of bridges are needing major repair. It is thought that the main reason for this problem is the shortage in the public capital invested in bridge maintenance during the last three decades [2]. In contrast with the U.S.A., the public capital investments for roads and bridges in Japan are still used in new construction works and less budget is allocated for maintenance. However, the large number of structures that have been built during the economic growth in Japan are getting old. Therefore, budget needed for repairing and renewing these structures should be increased.

Based on this background, there have been some trials to improve bridge maintenance by developing databases that facilitate the processing of bridge maintenance data. However, conventional relational databases can not process the geographical data and image data effectively and have limitations in expressing the bridge structure and management data. In this research, a prototype database system is developed that aims to overcome these limitations. This system uses new information technologies and represents a new type of bridge management information systems.

2. THE STRUCTURE OF THE SYSTEM

The suggested prototype database system has three modules: Geographic Information System (GIS) [6] module, object-oriented database module, and static and dynamic image processing module. Fig. 1 shows the structure of the system. In the following paragraphs, the data used in each module are explained.

1. Geographical data:

   The geographical data that can effect the bridge such as of the soils, road network, and rivers' data are added to the database system so that spatial analysis can be done using these data. The information of location and shape are represented using independent coverages. ARC/INFO (Environmental Systems Research Institute, Inc.), a workstation-based GIS, is used for the development of the system [3].

2. Bridge structure and maintenance data:

   The object-oriented representation of the bridge structure and maintenance data in the database is investigated. At the time being, this module has only the basic functions of the database system such as creating, deleting and retrieving objects. The bridge objects database can be used independently or it can be accessed through the bridge coverage of the GIS module.

3. Static and dynamic image data:

   Static and dynamic images can be used to visualize the details of the bridge and to clarify the type of damages. Pictures and video recording are input to the database and made accessible through the static and dynamic image processing module. The images related to each object of the bridge are added as attributes of this object that can be retrieved. For instance, the image of the superstructure at the time of the inspection is added as an attribute to the inspection object and can be retrieved as a part of the inspection data.

It may be possible to use the previous data during the whole bridge life cycle from the planning stage to the management stage. In the rest of this paper, each of the three modules of the system will be discussed in detail.

3. GIS-BASED BRIDGE MANAGEMENT SYSTEM

3.1 Merits of Using GIS for Bridge Management

Recently, many researches have been made about the applications of GIS in planning. In the field of bridge planning, a research has been carried out about the effective use of GIS for bridge planning

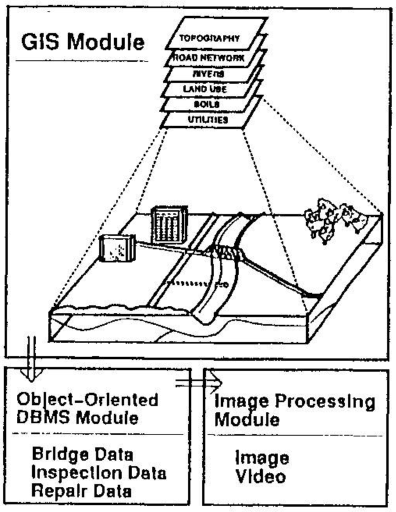


Fig.1 System structure

[5]. GIS software offers spatial analysis and statistical analysis capabilities by integrating graphic processing and database functionalities with a powerful user interface. The graphical information of the map can be represented by raster or vector format. In the case of the vector format, the information related to the graphical features can be expressed by numbers and character strings that form a database.

In this research, the geographical factors that can effect the bridge structure during its life cycle such as the soils, road network, and rivers'data are represented by independent coverages. These coverages can be overlayed and intersected in the process of spatial analysis. This paper discusses only the usage of the GIS coverages for maintenance purposes. However, it is believed that the same coverages can be useful for the life cycle bridge management because they include a variety of data that is necessary for bridge planning, maintenance, and management in general. By following this integration, the following goals can be reached:

1. Integrating the maintenance of all the bridges within a specific area.
2. Clarifying the mutual relation in the maintenance of a road and the bridge (or bridges) within this road.
3. Visualizing the geographical data that may influence bridge management.

In order to check the applicability of GIS in bridge management, a case study including 50 bridges of Nagoya city in Japan has been carried out. The data of the bridge inventory and other data needed for the bridge management are input to the system. The selected bridges are steel and concrete girder bridges. The range of bridge lengthes is between 10 m and 500 m, and the construction year is between 1931 and 1990.

Fig. shows an example of the geographical data that have been added to the system. The data of the bridges, road network, rivers, soils, etc. have been overlayed in one map. This kind of representation allows linking location's data and features' data in the coverages, and therefor, it allows matching several coverages in a way that is useful for bridge management. A menu-driven interactive user interface for data retrieval and spatial analysis has been developed with the programming language of ARC/INFO.

3.2 Data Collection and Pre-Processing

The main geographical data coverages considered in this research are: bridges coverage, road network coverage, rivers coverage, and soils coverage. In the following paragraphes, each of these coverages is discussed briefly.

1. Bridges coverage: This coverage contains the location and the main dimensions of the bridges such as the length and the width. The data of the bridge structure and the inspection are represented in an object-oriented database and will be discussed later.

2. Road network coverage: This coverage has the layout of the national roads, the expressways, and the other main roads in Nagoya city. The main attributes of this coverage are the grade of the road, its effective width, and the amount of its traffic flow.

3. Rivers coverage: This coverage can be especially useful in the bridge planning stage for deciding the width of the river, the high water level, and the flood level at the bridge location. The outline and the centerline of the 14 rivers in Nagoya city are digitized, and the attributes are registered and made retrievable through the centerline coverage.

4. Soils coverage: All the data of *New Nagoya Soils Database* [4] are imported to the GIS system. The data include the information of 4190 borings. The main factors that effect the selection of the bridge foundations are the standard penetration test result (N-value) and the deformation coefficient E. GIS can represent coverages in 2 dimensions only. Therefore, in order to represent the third dimension of the soils data, the depth information are added in a manner that allows the retrieval of the soil strength at the foundation depth. For instance, in the planning stage of a new bridge, the boring data near the potential location of the bridge can be used in the preliminary design of the foundation. Fig. 3 shows the boring locations near the rivers in Nagoya city. This retrieval is done by first creating a 200 m wide buffer around the centerline of the rivers, and then intersecting this buffer with the coverage of the boring locations.

   The original data of Nagoya soils database are divided into a mesh of about 100 m step. The boring data within a 140 m × 115 m square area in the mesh represent the whole of this area. Therefore, the data retrieved from the database in the planning stage may be up to 100 m far from the real location, and it is necessary to use engineering judgment when using these data. Figs. 4(a) and 4(b) show the comparison between the soil database and the inspection data from the bridge inventory at two points A and B. The solid line shows the soil data from the database while the dotted line shows the real inspection data. In the case of point A, the data of the database are very near to those of the inspection. However, in the case of point B there is some difference which means that the data of the boring database should be used as an approximate pointer about the soil type. The degree of the approximation depends on the number and the distribution of the boring points, i.e. if the boring data show that changes in the soil properties are small over a sufficiently wide area around the point under consideration, then the data of the soil at this point can be reliably used.

3.3 Examples of Spatial Analysis Using GIS

Two examples are given to show the advantages of using GIS within the bridge management system.

1. GIS can be used to clarify the relationship between the road and the bridge. For this purpose, the proposed system makes it possible to retrieve all the bridges in the same road or crossing the same river, or that satisfy other combinations of spatial conditions. For instance, retrieving all the bridges in a specific region with high traffic flow and that have not been repaired yet. Fig. 5 shows the result of the previous retrieval. In this example, the bridges within the specific region are retrieved first, then the bridges with traffic flow more than 10,000 cars/12h and with no repair are selected from them.

2. In the case of a disaster or during the repair of a river-crossing bridge, this bridge goes out of function and there should be alternative bridges to be used to cross the river instead of the

Fig.2 The different geographical data

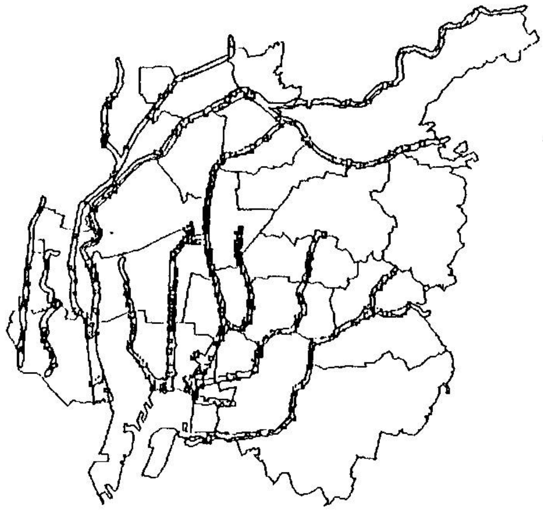


Fig.3 Boring points near the rivers

damaged bridge. These bridges should be near the bridge in question and should be able to resist the same design load. By retrieving the bridges that satisfy these conditions, it is possible to find alternative routes during the closing of the bridge. Fig. 6 shows an example of this case with a buffer of 1km around the bridges.

These examples show that complicated spatial retrievals can be done for items that are not explicitly defined in the bridge management system by overlaying several coverages. To be able to do the same retrieval in conventional bridge management systems, all the related attributes should be predefined in the database. Using GIS allows for doing spatial analysis, integrating the different data, and visualizing the results of the analysis.

4. OBJECT-ORIENTED DESCRIPTION OF BRIDGE INFORMATION

In the previous sub-section, the benefits of using GIS for representing the bridge-related geographical information have been discussed. In this sub-section, the representation method of the bridge data itself is discussed.

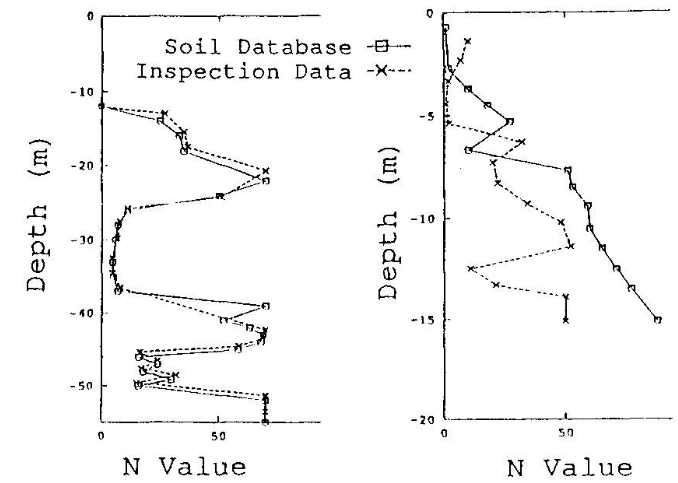
In 1991, in order to evaluate the state of the bridges in Japan and to provide the materials necessary to rationalize bridge maintenance, the Japanese Ministry of Construction ordered the local authorities to inspect the bridges within their areas. In this occasion, a new bridge management database system has been developed aiming to facilitate the exchange of data between the planning departments and to the higher authorities. This system is adopted as a model all over Japan [1]. The main items in the database are:

1. Bridge Inspection Main Data:

   These data contain the items usually found in the bridge inventory database such as bridge length, bridge width, type of foundation, bridge location, construction date, traffic flow, etc.

2. Superstructure Inspection Data:

   The existence of damage in the members of each span of the bridge according to the type and the material of the members are registered within these data. The name of the member and the counter-measures against the damage are also registered. The information related to the span number, the member name, and the type of damage are added by their code values. These data are used in the evaluation of the necessity of reapir.



(a) Point A (b) Point B

Fig.4 Comparison of standard penetration test values

3. Sub-Structure Inspection Data:

   The data of the sub-structure are similar to those of the superstructure.

4. Evaluation Result Data:

   This part has the result of the evaluation of inspection data and the necessity for repair for each member in the super- and sub-structure.

5. Repair History Data:

   Repair history data include the year and the method of the repair, the cost of the repair, etc. Fig. 7 shows the repair years of the 50 bridges used in the case study of this research. The figure shows that 20 bridges only have been repaired and that some of these bridges have been repaired more than one time. The repair method is given by its code and special repair cases are described briefly by a character string comment. Most of the repair cases are because of structural deficiencies of the bridge.

This database system is implemented on a personal computer using the relational database management system (DBMS) dBASE-III. Relational DBMSs are expressed by related tables and they can express only data that fit within the fixed table format. However, bridge inventory data and bridge inspection data are complicated and are difficult to fit within the relational DBMS. For instance, the items used in the bridge inspection may differ depending on the type and the material of the bridge. These items may differ even for the same bridge type when the number of spans changes. In order to overcome these problems, the object-oriented DBMS approach is used in this research to improve and expand the bridge management system.

The benefits of the object-oriented DBMS compared with the conventional relational DBMS are its flexible structure and the usage of the abstract data type called object. The object concept allows the representation of specific data (members) and abstract functions (methods) within similar objects. In addition, *inheritance* among objects is possible, i.e. the common parts of the data and functions are defined in the super-class while the more specific data and functions are added to the sub-classes without the need to redefine the common attributes. The $C++$ language is used for the implementation of the prototype [7].

Fig. 8 shows a part of the bridge structure object representation. This figure will be used also to compare the object-oriented DBMS and the relational DBMS, and to explain the merits of the former approach. In the relational bridge DBMS suggested by the Japanese Ministry of Construction, the

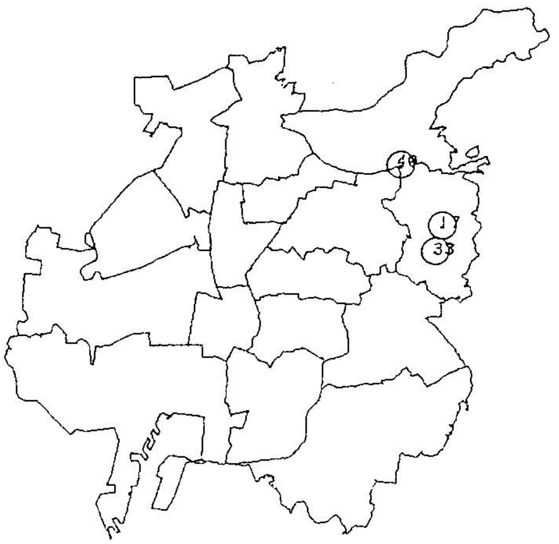


Fig.5 Retrieving bridges for maintenance

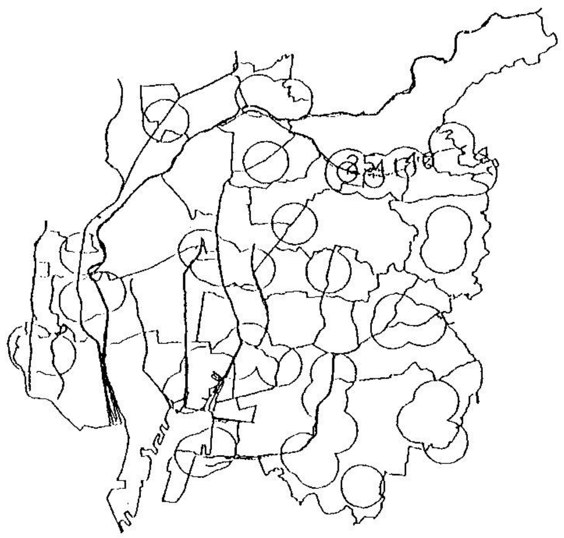


Fig.6 Retrieving alternative bridges

data of the bridge are represented by 5 tables (relations). With this respect, in the object-oriented bridge DBMS suggested in this research, the same data are represented by hierarchical objects that correspond to the structure of the bridge structure. In addition, the dimensions and the material of the bridge members and the related inspection and repair data are registered as attributes of the respective objects. Fig. 8 shows the object-oriented representation of the basic bridge data and superstructure and substructure inspection and repair data. The merits of using the object-oriented representation in the bridge management database are:

1. The extensibility of the bridge DBMS:

   The object-oriented representation of the bridge management database facilitates the management of the data. Consequently, including the bridge design data in the database (which is difficult with conventional database models) becomes possible and these data can be used to integrate the data used in all the stages of the life cycle of the bridge from the planning stage to the maintenance stage.

2. Emphasizing the bridge history data:

   In the bridge DBMS suggested by the Japanese Ministry of Construction, the time-dependent data of the inspection and repair history are registered first, and the names of the parts of inspection or repair are added, e.g. superstructure at span number 3. However, in the relational bridge DBMS, it is difficult to specify the exact place of damage, e.g. the upper flange of member 2 in girder 1. However, using the object-oriented approach to represent the bridge structure makes it possible to add the inspection and repair data periodically to the copies of the bridge objects. For instance, in case there is a repair work in the upper flange of the second member of the first girder, the details of the repair can be registered in an instance of the corresponding object.

5. INTRODUCING STATIC AND DYNAMIC IMAGE PROCESSING

In the present practice of bridge inspection, the detailed data related to the damage type in the bridge members such as cracks and rust, are documented not only as text explanation, but also by taking several pictures of the damage and arranging them in an album. These pictures are referred to

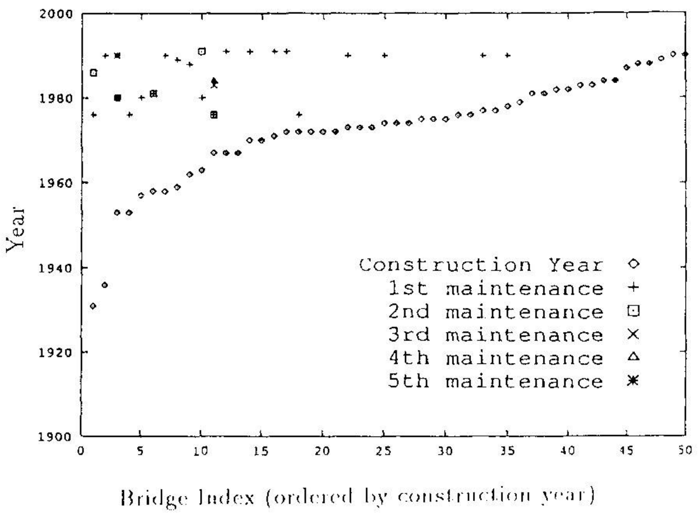


Fig.7 Repair years of the bridges

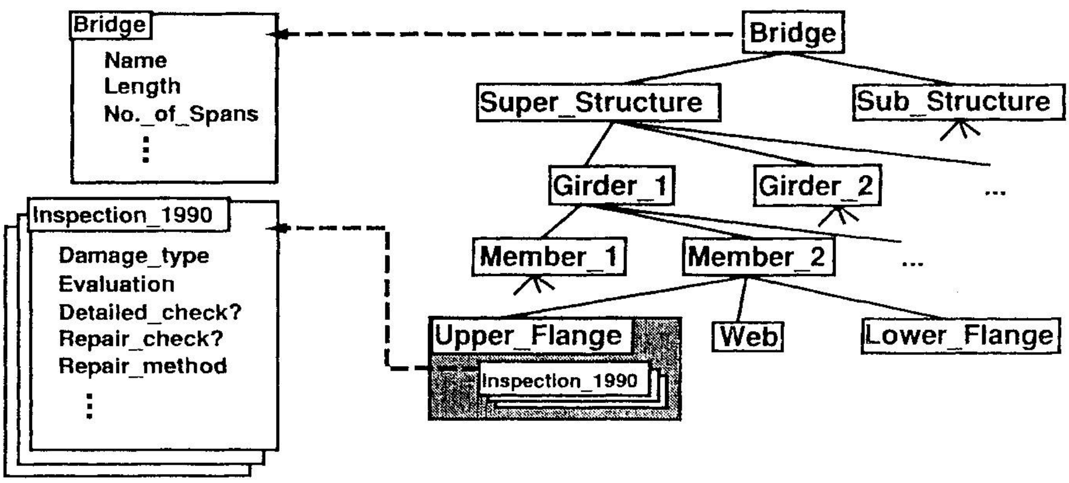


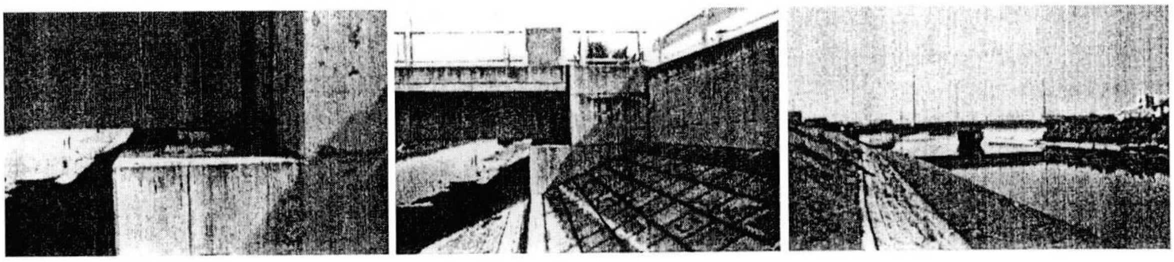
Fig.8 Example of the object-oriented representation of the bridge

later to help in the visual understanding of the damage pattern and damage place. The conventional bridge DBMS can usually handle only numbers and character strings and therefor, image data can be accessed only through an index corresponding to the file containing the image.

However, as a result of the recent development of computer technology, it is becoming possible to save and process image data in the computer effectively. In addition, combining graphics, character data, static and dynamic images, and sound data in an integrated multimedia environment that can appeal to the different human senses is becoming popular. For instance, in the field of civil engineering, images are introduced to road inspection system [8]. In this research, the application of new media such as static and dynamic images in the bridge management system is suggested.

1. Static image data: The static image data that are necessary for bridge management are:

   (a) Bridge general images: The role of these images is to help understanding the shape of the bridge in general. In this research, 3 images are scanned and saved for each bridge (profile image, image from the bottom, and image of the support). A comment explaining the



(a) Place of the Damage (b) Part of the Bridge (c) Total View of the Bridge

Fig.9 Example of retrieving the damaged place

characteristics of each image is added. These image data are registered as attributes of the bridge object.

(b) Images of the damaged parts: In order to grasp the place of the damaged parts and its relation to the whole bridge, many pictures showing gradually smaller scope are attached to the objects representing the members of the bridge in the object-oriented bridge DBMS. In addition, it is made possible to compare the images of the damage part before and after the damage. Retrieving the places of the damage starts by displaying the image focusing on the exact place of the damage. Then, a series of pictures are displayed in order to show the relative position of the damage in the whole bridge. The number of the images in one series is not fixed but 3 to 5 images would be usually enough. Fig. 9 shows a series of images showing the place of the damage in the abutment under the right support of the bridge.

Because image data usually need huge storage memory, it is necessary to decide the specifications concerning the quality of the image and its format so that these images can be accumulated and managed in the most economic and efficient manner. The images used in this research are scanned with an EPSON-GT8000 scanner and saved in TIFF format (Tagged Image File Format). TIFF format is adopted because it is more standard than other formats such as the SUN RASTER or the Macintosh PICT formats.

2. Dynamic image data: Using dynamic images, it becomes possible to visually record the steps used in the maintenance and repair in the shape of a short movie that can be replayed. However, dynamic image data need a huge memory when saved in the digital form on the harddisk, which is expensive. Therefore, in this research, two methods are proposed for processing dynamic image data.

   (a) Only the dynamic images of the damaged parts are saved in the digital form. A Macintosh Centris-660AV is used for inputing the images and they are saved in MPEG (Motion Picture Experts Group) format. The reason for chosing MPEG format is that it is more widely used standard than other formats and it has an efficient compression algorithm. Table 1 shows a summary of the methods used in manipulating static and dynamic images.

   (b) In the case of long video scene, the VCR tape is controlled by the computer. The video control device SONY Vbox-CI-1100 is connected to the computer with an RS-232C interface, and connected to the VCR (SONY SLV-RS7) with a LANC interface. The main functions of controlling the VCR are: play, rewind and forward, and search for a specific scene using the real time counter. This method of keeping the video data in its analog form is more economic than the digital video. However, the access time is long due to the sequential nature of the video tape.

	Static Images	Dynamic Images
Image Quality	100 dpi	20 frame/sec
No. of Colors	256	256
Size (pixel)	320 × 240	160 × 120
File Size	about 100 KB/image	about 6 MB/min
Format	TIFF	MPEG
Input Device	EPSON-GT8000	Centris-660AV
Saving Device	HD	VCR, MO, HD

Table 1 Summary of the methods used in manipulating images

6. CONCLUSIONS

Bridge management databases are becoming more widely used in the practical level. The new methodology presented in this paper to represent and process the bridge-related data is still in the first stage of application. However, it is expected that applying this methodology in future bridge management systems can give better results than the conventional bridge management databases in integrating the different data in one system. Such a system can be used for the life cycle management of all the bridges on the network level. The main conclusions of this paper are:

1. Using GIS within the bridge management system helps in integrating the geographical data that may influence the bridge maintenance process and in carrying out spatial analysis on this data, which is not possible in the conventional bridge management systems.
2. The object-oriented database approach proves to be efficient in representing bridge inventory data and bridge inspection and repair data.
3. The multimedia approach resulting of adding static and dynamic images is useful in the visual understanding of bridge management problems.

Some of the problems that have been faced in developing the proposed prototype system are:

1. In the GIS module, it is necessary to anticipate the different situations that need spatial analysis and to develop procedures to help the bridge management planners, who may not be familiar with computers, in using the system efficiently.
2. In the object-oriented database module, the method of representing the bridge design data needs further investigation.
3. Several problems remained to be solved about the efficient method for retrieving and comparing image data such as deciding the camera location for taking pictures, etc.

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An Associative Model for Damage Diagnosis of Existing Buildings

Modèle associatif pour le constat de dommages dans des bâtiments existants

Ein assoziatives Modell für die Schadensdiagnose an bestehenden Bauten

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SUMMARY
In many cases, damage phenomena are quite complex, and their causes may have different plausibility values. A knowledge-based associative model is introduced for coding more experience from domain experts. The present model can be used to obtain a number of possible damage causes and also to show the plausibility value for each damage cause. The model has already been applied in an expert system called "Reliability Assessment In Structural Engineering which has been recommended by the State Ministry of Construction of China.

RÉSUMÉ
Il n'est pas toujours possible d'établir des relations causales entre un dommage observé et ses causes. Pour les cas où plusieurs valeurs plausibles existent pour l'origine des dommages, un modèle associatif à base de connaissance a été réalisé, prenant en compte l'expérience des spécialistes. Le modèle donne la plausibilité pour chaque cause de dommage et son usage a été recommandé comme système expert en Chine.

ZUSAMMENFASSUNG
Nicht immer lassen sich für die Schadensdiagnose einfache kausale Beziehungen zwischen beobachtetem Schaden und seiner Ursache herstellen. Für den Fall, dass mehrere plausible Werte für Schadensursachen existieren, wurde ein wissensbasiertes, assoziatives Modell eingeführt, um mehr Erfahrung von Fachexperten zu kodieren. Das Modell gibt die Plausibilität für jede Schadensursache an und wurde als Expertensystem *in China empfohlen.*

1. INTRODUCTION

It is well known that the knowledge on damage diagnosis of existing buildings is dependent on the particular expert who has his own experience from his career and the diagnostic methodology for one expert is also quite different from others[1][2]. After collecting enough knowledge it is easy to find that the knowledge on damage diagnosis could be grouped into two ways, which can be expressed as follows.

(a) For more simple damage phenomena there may be only one or two causes existing. In this case, domain experts may use a hard mapping , such as "if A then B", to do the diagnosis. Here A means the damage phenomenon and B means the damage cause.

(b) For more complex damage phenomena more damage causes may exist. In this case, domain experts may consider their characteristics, and based on some association, may use a soft mapping, such as "if $A_1, A_2, A_3, \ldots$, then$B_1, B_2, B_3, \ldots$ ". Even then, it is also possible to give a plausibility for each damage cause by experience from domain experts.

Most expert systems for damage diagnosis or assessment of existing buildings are using the first simple way. Its advantages are obvious. Such as, it is easy to acquire knowledge and to build a knowledge base. The reasoning method is also relatively simple. But for more complex damage phenomena, the most plausible cause among all the damage causes may not be easy to be obtained. Since the simple rule is too strict, which may not be able to express different diagnostic experience from different expert. To the end, an association model introduced in the present paper is needed.

Based on the present model all the possible damage causes can be obtained, and according to the diagnostic knowledge from domain experts the most plausible cause can eventually be obtained. In fact, the first way using simple rules is a particular case of the introduced association model. This model has already been performed in an expert system called "**R**eliability **A**ssessment **I**n **S**tructural **E**ngineering (**RAISE**-3 and **RAISE**-4)"[3][4][5], which has been recommended by the State Ministry of Construction of China.

2. AN ASSOCIATION MODEL FOR DAMAGE DIAGNOSIS

Assume that $M_1, M_2, \ldots, M_n$ to be the various damage modes; $K_{c\_1}, K_{c\_2}, \ldots, K_{c\_m}$ to be the various kits of damage causes; and $C_{1\_1}, C_{1\_2}, \ldots, C_{2\_1}, C_{2\_2}, \ldots, C_{m\_1}, C_{m\_2}, \ldots$ to be the various damage causes.

Call the set $MD\_S = \{M_1, M_2, \ldots, M_n\}$ to be the set of damage modes; $KC - S = \{K_{c\_1}, K_{c\_2}, \ldots, K_{c\_m}\}$ to be the set of damage cause kits ; and

$C\_S = \{C_{1\_1}, C_{1\_2}, \ldots, C_{2\_1}, C_{2\_2}, \ldots, C_{m\_1}, C_{m\_2}, \ldots\}$ to be the set of damage causes. Each of damage cause kits includes a number of the damage causes, such as

$$K_{C\_X} = \{C_{X\_1}, C_{X\_2}, \ldots\} \quad (X = 1, 2, \ldots, m).$$

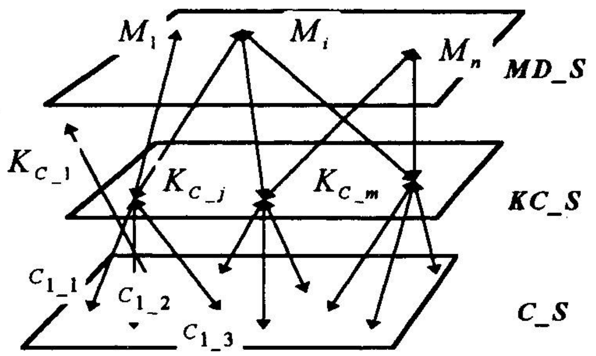

Fig. 1 The Association Model

The relationship between *MD_S*, *KC_S*, and *C_S* is shown in Fig.1. According to this model, any given element $M_i (i = 1,2,...,n)$ from the set of damage modes, *MD_S*, can be connected with several kits in the set of *KC_S* by association. On the other side, any given damage cause kit $K_{C\_j} (j = 1,2,...,m)$ from *KC_S* can also be connected with several damage modes from *MD_S* by association, and furthermore, they also can be connected with several damage causes from the set *C_S* by association as well. In other words, any element in the set of damage modes, *MD_S*, can be connected not only with elements in the set of damage cause kits (*KC_S*) directly but also with elements in the set of damage causes (*C_S*) indirectly. It means that, by association, it is possible to obtain all damage causes for any damage mode . Also, it is possible to obtain all damage modes for any damage cause by association.

In general, a damage phenomenon does not mean only one damage mode happened. Usually it includes several modes. Using the present association model all the possible damage causes for the several damage modes in a same damage phenomenon can be obtained. In order to determine the most plausible damage cause from a damage phenomenon the concepts on the plausibility of a damage cause, the medium set of damage modes, the medium set of a damage phenomenon, the intersection of the medium sets, and the union of the medium sets should be defined first, which will be introduced as follows.

3. THE PLAUSIBILITY OF DAMAGE CAUSES

As explained previously, any damage mode , in the most cases, can not be induced by one cause only. Among all the causes, some of them have higher possibility and some of them have lower. In the present paper, the plausibility is used to describe the possibility of a damage cause which induced a certain damage mode. It means that, for a certain damage cause, the higher possibility the higher plausibility and vice versa. At present, two different definitions on the plausibility should be introduced first.

(1) Plausibility A_{ij} : to describe the possibility of that the damage mode M_i is caused by the damage cause kit K_{C_j}.

(2) Plausibility a_{ijk} : to describe the possibility of that the damage mode M_i is caused by the damage cause C_{j_k} from the damage cause kit K_{C_j}.

In fact, the plausibility is a fuzzy measurement in the damage diagnosis. For different damage phenomena the plausibility values of the same damage cause kit (or of the same damage cause) may be different. Even for the same damage mode in the same damage phenomenon the plausibility values for different domain experts are different. In general, the plausibility can change between a certain interval. In RAISE-3 and RAISE-4, according to the experts' experience, the plausibility interval is chosen as [0,1].

4. THE MEDIUM SET, INTERSECTION, AND UNION

The medium set of a damage mode means a set, which includes all the possible damage cause kits for the damage mode and their plausibility values. The medium set of a damage phenomenon means a set of all the medium sets of the possible damage modes. They can be obtained as follows.

4.1 The Medium Set of a Damage Mode M_i

As shown in Fig. 1, all the possible damage causes of M_i, such as $K_{C\_1}, K_{C\_2}, \ldots$ can be obtained by association. According to the knowledge from domain experts the plausibility values of $K_{C\_1}, K_{C\_2}, \ldots$, such as $A_{i1}, A_{i2}, \ldots$, also can be determined. Thus, the medium set of damage modes MM_S_i can be expressed as

$$MM\_S_i = \{(K_{C\_1}, A_{i1}), (K_{C\_2}, A_{i2}), \ldots\} \quad (1)$$

which is called the medium set of a damage mode M_i.

4.2 The Medium Set of a Damage Phenomenon App_i

It is assumed that a damage phenomenon App_i is consists of a number of damage modes, such as $M_1, M_2, \ldots, M_d$ (in Fig. 1, d usually is less than n). There is a set,

$$AM\_S_i = \{MM\_S_1, MM\_S_2, \ldots, MM\_S_d\} \quad (2)$$

which is called the medium set of the damage phenomenon App_i.

Unlike the classical definitions , the concepts on intersection and union used here have some different meanings, which can be shown as follows.

4.3 The Intersection of Medium Sets

Since the damage phenomenon App_i consists of several damage modes $M_i(i=1,2,...,d)$, the intersections between the medium sets of the damage modes $M_i(i=1,2,...,d)$, i.e. $MM\_S_i(i=1,2,...,d)$, and the medium set AM_S_i of App_i can be obtained respectively, by the following way.

(a) According to the association model shown in Fig.1 and considering the plausibility values find the medium sets of damage modes $M_i(i=1,2,...,d)$ as Eg. (1).

(b) As introduced previously, find the medium set of damage phenomenon App_i as Eg. (2).

(c) Compare each element of MM_S_i $(i=1,2,...,d)$ with elements of AM_S_i , respectively. If one of $K_{C\_j}(j=1,2,...,m)$ appears in t elements of AM_S_i and t $(t \le d)$ is bigger enough, which means that it may cause the most damage modes in App_i , then this K_{C_j} and its plausibility can be treated as one element in the intersection. Otherwise take the next MM_S_i to continue. Finally the intersection between MM_S_i $(i=1,2,...,d)$ and the medium set AM_S_i of App_i can be done. It can be called IS_i .

4.4 The Union of Medium Sets

Among the damage modes $M_i(i=1,2,...,d)$ of App_i such a damage mode always exists: when it appears, its major cause or a few of causes of it can be confirmed. It means that for some damage modes the numbers of possible damage causes are very limited and they are easy to be determined. In this case, such damage mode in App_i should be considered as **"more important"** and its weight also should be bigger than others. If there are many damage causes for a damage mode, and they are also different from those of other damage modes, then such damage mode is considered as **"not so important"** and may have smaller weight. Based on this consideration, the importance order of $M_i(i=1,2,...,d)$ in App_i can be done by domain experts. The union can be obtained as follows.

(a) Rearranging the damage modes $M_i(i=1,2,...,d)$ in App_i by their importance order and assuming that the importance order of $M_i(i=1,2,...,d)$ in App_i has been done as the original order, the medium set of App_i will be the same as Eq.(2).

(b) Find the intersection between MM_S of the damage mode M_1 and the medium set AM_S_i of App_i , i.e. ,

$$IS\_1 = \{...,(K_{C\_j}, A_{1j}),....\} \quad (j \le m) \tag{3}$$

Rearranging the elements (K_{C_j}, A_{1j}) in IS_1 by the order of A_{1j} a new set MS_i is obtained. Herein it is assumed that the order of elements in IS_1 is the same as in MS_i .

(c) Find the rest of intersections between $MM\_S_i (i=2,...,d)$ of the damage modes $M_i (i=2,...,d)$ and the medium set AM_S_i of App_i, respectively. They are, $IS_2,...,IS_d$. Rearrange the elements (K_{C_j}, A_{ij}) in $IS_2,...,IS_d$ by the order of their plausibility values.

(d) Compare the elements in $IS\_i (i=2,...,d)$ with those in MS_i, respectively. If the element (K_{C_j}, A_{ij}) has appeared in MS_i already, then there is no need to modify MS_i . Otherwise the mentioned element (K_{C_j}, A_{ij}) should be treated as a new element to be put on the tail in MS_i . Finally, the modified union MS_i can be done. It should be noted that the MS_i is also a medium set of App_i , but it is different from AM_S_i .

5. THE MOST PLAUSIBLE DAMAGE CAUSE

As mentioned previously, the order of chosen damage cause kits $K_{C\_i} (i \le m)$ in MS_i, is determined by their plausibility values. Thus, the most plausible damage cause for the damage phenomenon App_i can be inferred by the following way.

(a) According to the given damage phenomenon App_i to find the medium set MS_i.

$$MS_i = \{....,(K_{C\_j}, A_{ij}),....\} \quad (i=1,...,d; j \le m) \tag{4}$$

(b) Following Fig.1 to find all the damage causes $C_{j\_1}, C_{j\_2},...$ for each of the K_{C_j} in MS_i .

(c) Find the most plausible damage cause among $C_{1\_1}, C_{1\_2},...$, which causes the first damage mode M_1 in App_i . If there is no possibility to cause M_1 by $C_{1\_1}, C_{1\_2},...$, then do the same for the second damage mode M_2 . Similarly it can be done for other damage modes. Finally the most plausible damage cause C_{i_x} for some damage mode should be certainly obtained.

(d) According to Fig.1 check the number of damage modes in App_i, which are caused by C_{i_x} . If the number r is bigger than a certain value (it can be determined by domain experts) then the damage cause C_{i_x} can be considered as the most plausible damage cause for the damage phenomenon App_i . In this case, the chosen C_{i_x} also can be shown to users to confirm it.

(e) If the number r is less than the required value or users do not agree with the chosen C_{i_x}, then we can continue to find it among the others of $C_{j\_1}, C_{j\_2}, \dots$. If we can not find the most plausible damage cause from K_{C_j}, then we can continue to do the same process for $K_{C\_(j+1)}, K_{C\_(j+2)}, \dots$.

In general, following the mentioned steps, the most plausible damage cause should be diagnosed, which can be seen in the following example.

6. EXAMPLE

Assume that a damage phenomenon $App_{\_1}$ is found in a reinforced concrete industrial workshop and the damage phenomenon consists of four damage modes, such as M_1, M_2, M_3, M_4 (here $d=4$), which are: M_1 Diagonal cracks on the wall closed to both ends of the workshop; M_2 Horizontal cracks on the internal sides closed to the columns' bottom; M_3 Vertical cracks on the lower wall; and M_4 Squeeze between Rail and crane wheels (Fig.2).

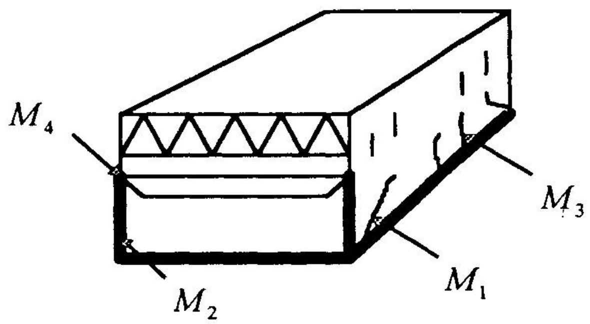

Fig.2 A Damage Phenomenon $App_{\_1}$

Also assume that the association mode for damage diagnosis of the present building has been made and all the plausible damage cause kits in the present case are known (as shown in Fig.1 $m=4$), which are: K_{C_1}: Foundation ; K_{C_2}: Temperature ; K_{C_3} : Construction ; K_{C_4} : Load . Thus, the diagnostic process can be done as follows.

(a) Based on the mentioned association model, such as shown in Fig.1, and according to the related plausibility values known from domain experts, the medium sets of the damage modes, as explained in Section 4.1, can be obtained. In the following parentheses, the first term means the plausible damage cause kit and the second term means its plausibility. They are,

M_1 $\quad MM\_S_1$={(Foundation, 0.8), (Temperature, 0.7)}

M_2 MM_S_2={(Construction, 0.6), (Foundation, 0.5), (Load, 0.55)}
M_3 MM_S_3={(Foundation, 0.7), (Temperature, 0.6), (Load, 0.3)}
M_4 MM_S_4={(Load, 0.6), (Foundation, 0.3), (Construction, 0.4)} .

(b) The medium set of the present damage phenomenon App_1 can be found as shown in Section 4.2, which is,

$AM-S_1 = \{MM-S_1, MM-S_2, MM-S_3, MM-S_4$
= {((Foundation, 0.8), (Temperature, 0.7),
((Construction, 0.6), (Foundation, 0.5), (Load, 0.55)),
((Foundation, 0.7), (Temperature, 0.6), (Load, 0.3)),
((Load, 0.6), (Foundation, 0.3), (Construction, 0.4))}

(c) According to Section 4.3 the intersections between the medium sets $MM\_S_i (i = 1,2,3,4)$ of damage modes $M_i (i = 1,2,3,4)$ and the medium set AM_S_1 of App_1 can be obtained respectively. They are,

IS_1 = {(Foundation, 0.8)}
IS_2 = {(Foundation, 0.5), (Load, 0.55)}
IS_3 = {(Foundation, 0.7), (Load, 0.3)}
IS_4 = {(Load, 0.6), (Foundation, 0.3)} .
It should be noted that, as mentioned in Section 4.3(c), t is taken as 3.

(d) As explained in Section 4.4, the importance order of damage modes of App_1 should be: M_1, M_3, M_2, M_4 . In this case, following Section 4.4 (b) (c) (d), the union should be

MS_1= ((Foundation, 0.8), (Load, 0.3))

(e) At this step, the most plausible damage cause of App_1 can be inferred . Since the association model has bee given, the damage causes contacted with the foundation problem and the load problem should be known. Their related damage modes and corresponding plausibility values can be shown as follows.

Foundation K_{C_1}

C_{1_1} Uneven settlement
$(M_1, 0.8), (M_3, 0.5), (M_2, 0.3)$

C_{1_2} Soil freeze-thaw
$(M_2, 0.4), (M_1, 0.3), (M_4, 0.1)$

		C_{1_3}	Soil holes $(M_4,0.3),(M_3,0.5),(M_2,0.4)$
Load	K_{C_4}	C_{4_1}	Overloading horizontally $(M_2,0.6),(M_3,0.15),(M_4,0.3)$
		C_{4_2}	Overloading vertically $(M_2,0.1),(M_3,0.5),(M_4,0.6)$

According to MS_1, It is known that the most plausible damage cause for the damage phenomenon $App_{\_1}$ should be found among the damage causes of the foundation, i.e. K_{C_1}. The inference process is shown as follows.

(a) As explained in Section 5(c) previously, among $C_{1\_1}, C_{1\_2}, C_{1\_3}$, the most plausible damage cause to induce the damage mode M_1 is C_{1_1}. In this case, it is assumed that C_{1_1} is also the most plausible damage cause for the given damage phenomenon $App_{\_1}$.

(b) Following Section 5(d), since C_{1_1} causes three damage modes, i.e. M_1, M_2, M_3 (in this case *r=3*), it can be considered as the most plausible damage cause for $App_{\_1}$, and send it to users to confirm it.

(c) If users do not agree with C_{1_1}, then the most plausible damage causes also can be found from C_{1_2}, C_{1_3} by the bigger plausibility values of M_1. Thus, C_{1_2}(with *r=3*) can be found. Similarly, it should be sent to users also.

(d) If users still refuse to agree with it, then the same process can be done for M_3, M_2, M_4, respectively. In this case, C_{1_3}(with *r=3*) should be found.

(e) If it is impossible to find the most plausible damage cause from the foundation problem (in the damage cause kit K_{C_1}), then following the order M_1, M_3, M_2, M_4, the same process can be done in K_{C_4} (loading problem). Similarly, C_{4_2} and C_{4_1} can be found.

The final diagnostic result for the damage phenomenon shown in Fig.2 should be in the following plausibility order: *Uneven settlement of foundation, Soil freeze-thaw of foundation, Soil holes of foundation*. If there is no problem on foundation. The damage causes may be *Overloading vertically*, or *Overloading horizontally*.

7. REMARKS

Obviously, the structure of the association model and its relative plausibility values should be determined by domain experts first. Comparing with the simple rule "if *A* then *B*" it is more general. It also should be mentioned that unlike neural network models[6][7] the present model can code the diagnostic experience in explicit form. Therefore, It is more efficient in practice. Besides, it is very flexible to improve the model structure and plausibility values for coding new knowledge.

The present model, as one of useful models, has already been used in an expert system called "Reliability Assessment in Structural Engineering"(RAISE). It was written in GCLISP and FROTRAN under windows. There are two versions available: RAISE-3 (English version) and RAISE-4(Chinese version). According to the assessment results from 160,000 M^2 existing industrial building, the comparison between system RAISE and experienced engineer is very satisfactory. RAISE with the present association model has been recommended by the state Ministry of Construction of China since 1994.

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Application of a Knowledge Support System to Dam Safety: a User Report

Application d'un système expert pour la sécurité d'un barrage

Anwendungsbericht über ein wissensbasiertes Staumauerüberwachungssystem

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SUMMARY

The article describes the experience of the user in the automatic monitoring and risk assessment of the Ridracoli Dam, using a knowledge support system for the on-line interpretation of the dam's behaviour. Data collected by a complex monitoring system is continuously processed and interpreted by the knowledge support system in order to support the Safety Manager in the surveillance of the evolution of the behaviour of the structure and of its foundation.

RÉSUMÉ

L'article décrit l'expérience acquise par un utilisateur dans le domaine de la surveillance automatique et de l'évaluation des risques du barrage de Ridracoli. Il s'agit d'un système expert pour l'interprétation en temps réel du comportement du barrage. Le système exploite de façon continue les données récoltées par un système complexe afin d'aider le responsable de la sécurité dans la surveillance de l'évolution du comportement du barrage et de sa fondation.

ZUSAMMENFASSUNG

Der Beitrag beschreibt die Erfahrung in der Benutzung eines On-Line-Systems zur automatischen Ueberwachung und Gefährdungsbeurteilung der Ridracoli-Staumauer. Die vom komplexen Erfassungssystem gesammelten Daten werden kontinuierlich ausgewertet und durch ein wissensbasiertes System interpretiert, um den Sicherheitsbeauftragten bei der Ueberwachung des Verhaltens von Staumauer und Untergrund zu unterstützen.

1. INTRODUCTION

The collection, storage and analysis of information concerning a dam are a critical part of managing safety of the structure. An important part of the management of this information is the interpretation of data coming from the monitoring. In addition the use of automatic instrumentation and data storage in dam monitoring has resulted in large amounts of data requiring analysis and interpretation. The use of knowledge support system for the on-line check of dam's behaviour is useful to reduce human time consuming and to request timely human intervention and analysis.

2. DESCRIPTION OF RIDRACOLI DAM

The Ridracoli arch-gravity concrete dam (height 103.5 m and crest length 432 m) closes a very wide U-shaped valley in the Tuscan-Romagna Apennines in Italy. The storage reservoir is intended for water supply to 37 communities in the Forli' and Ravenna Provinces, including the main towns and the San Marino Republic.
Ridracoli dam was completed in 1982 and subsequently the experimental storages started following a program of water level steps with the aim of analyzing creep deformation, anelastic settlements and displacements of the dam and of the rock foundation due to water level and thermal variations. The reservoir was filled completely for the first time in 1986 and nowadays the dam is going to be commissioned for normal operation.

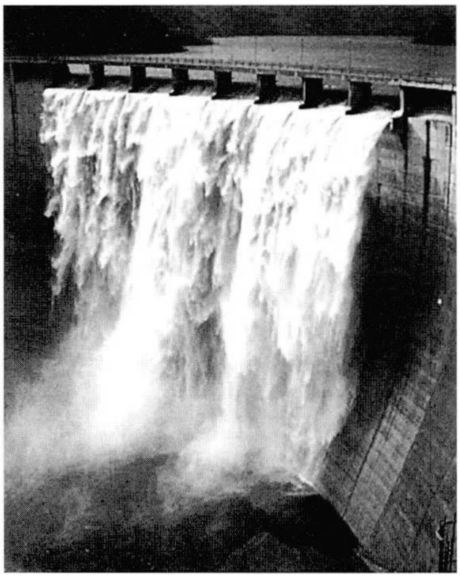


Fig.1 -View of the Ridracoli dam

3. THE AUTOMATIC MONITORING SYSTEM

To control the Ridracoli dam structure, the foundation, the reservoir banks and the slopes of the downstream rocky formation a large monitoring network has been installed during the construction. The reading, centralized in the warden house via cable, of most of the measurements (259 on a total of 971) is realized by an automatic monitoring system. Many instruments were installed for a detailed monitoring of the structure's behaviour during construction and first filling phase. In the current normal operation, the surveillance of dam performance is obviously based on a limited subset of measurements.
The instrumentation network makes it possible to acquire the most important "cause" quantities (water level, air, water and concrete temperatures, meteorological quantities) and "effect" quantities on the dam and its foundation (vertical and planimetric displacements, stresses and deformations, rotations, movements of the joints, seepage, uplift pressures in the foundation, fault control behaviour, water table in the abutment).

4. OFF-LINE MANAGEMENT AND BEHAVIOUR ANALYSIS

Measurements, automatically or manually recorded, have been periodically stored into the historical data bank and processed to analyze the dam's behaviour. During the design phase a three dimensional F.E. model has been set up in order to predict the theoretical behaviour caused by water level and thermal variations (Fig.2). Starting from the beginning of the first filling of the reservoir the theoretical model has been used as reference to check in time the behaviour of the dam.

The behaviour analysis carried out has pointed out the occurrence of cyclic phenomena, with seasonal period mainly linked to water level and temperature variations, and anelastic phenomena correlated to the first fillings. Dam displacements fully comply with the forecasted theoretical displacements. This analysis also made it possible to check the logical consistency of the information provided by different instruments affected by the same phenomena.

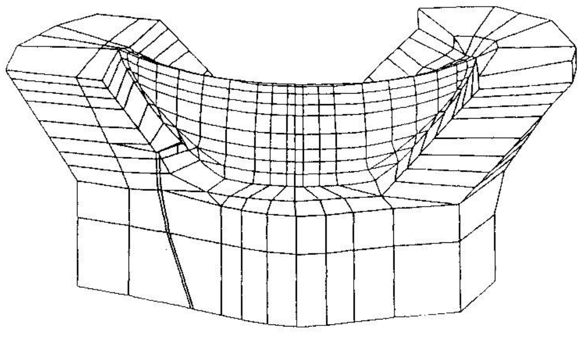


Fig.2 - 3D F.E. model of the dam

5. ON-LINE CONTROL

During the off-line activity, the parameters used for the on-line check have been determined (1987), and they are periodical verified. The theoretical model has been calibrated with reference to the measured behaviour and it is periodically used for in depth analysis of dam's behaviour.

The on-line surveillance during operation is mainly based on 32 measured quantities.

Since 1987 the most important measurements are tested against threshold values and theoretical behaviour predicted by the reference model. For each measurement that is not consistent with the reference values a warning message is generated.

A knowledge support system (named **Mistral**) has been installed in 1992 on a personal computer connected to the automatic monitoring system in the acquisition center located in the warden house near the dam. Mistral is a knowledge based system for evaluating, explaining and filtering the information collected by the most important instruments connected to the automatic monitoring system, providing on-line interpretation of the behaviour of the structure in order to support the activity of the personnel responsible of the safety surveillance.

The on-line system makes it possible to verify the state of each measurement with respect to threshold levels (physical threshold, measure rate of variation and reference structural model - Fig.3), using knowledge about significance and reliability of each instruments, and evaluates the current state of the dam and of any elementary structural part, identifying any anomalous process and verifying the reliability of the measurements by congruency checks.

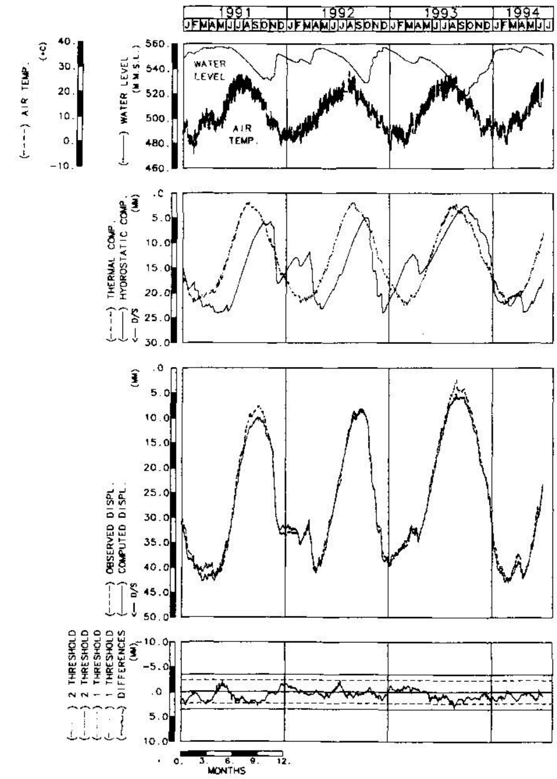
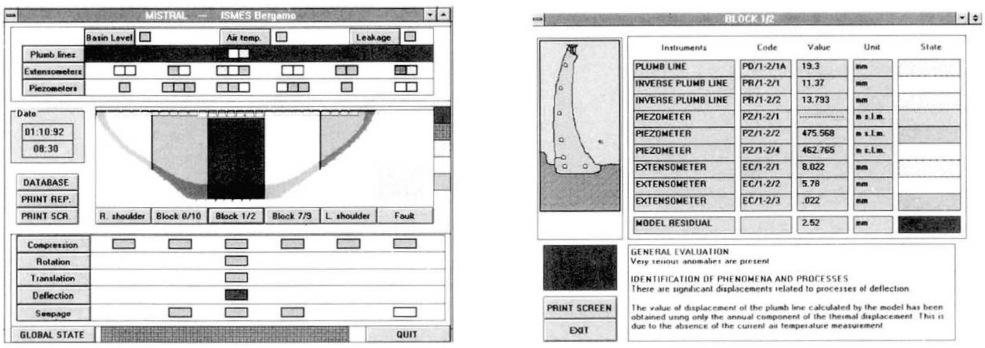


Fig.3 - Measured-Computed displacements

6. MISTRAL USE AND RESULTS

Mistral provides on-line interpretation of the behaviour of Ridracoli dam, evaluating, filtering and explaining the data collected by the automatic monitoring system in order to support the Safety Manager during the surveillance of the dam and requiring his intervention for anomalous situation. As scheduled in the surveillance activities, the technicians working at the warden house check daily

the information provided by Mistral verifying the state of the sensors and the results obtained by the analysis of the dam's behaviour, displayed through the colour-based graphical interface that represents the state of the measurements, of the processes, of each section and of the entire structure under evaluation and relevant explanation (Figg.4,5).
Mistral is a friendly program and obtained a very rapid acceptance by the user (1 day training).
If necessary the technicians use its functionalities to get more detailed information and enter to the local data base to compare the evolution of the dam state in time.
If any signalling or warning is reported on the display, the technicians have to verify the proper functioning of the signalled instrumentations and perform a visual inspection of the zone pointed out and in case of anomalous situation request the Safety Manager intervention for in depth analysis.



Figg 4,5 - Mistral Interfaces (general state of the dam and the expansion for the main section)

Mistral performs on-line check every hour and from its installation till now has analyzed more than 15000 situations (about 580000 instrument data). From 1992, running Mistral the following issues were pointed out:

- Wrong data are properly filtered by congruency checks avoiding incorrect signalling. The validation data process recognized errors in data due to wrong signals for about 0.5 percent of the examined measurements.
- Instrumentation problems due to anomalous functioning of some sensors, such as piezometers in rock foundation and one potenziometric transducer installed on the rockmeter installation. Mistral gives the possibility to request and perform prompt maintenance interventions to the sensors, with no delay in time.
- The basic parameters implemented in Mistral (threshold values, parameters of the reference model, parameters synthesizing the significance and reliability of each instrument) have been confirmed and did not need any update.
- The behaviour of the structure complies with the forecasted values computed by the theoretical reference model, without identification of any anomalous process, confirming that the dam and its foundation behave in elastic manner.

The two years of experience in the use of the knowledge support system have provided valuable verification of its effectiveness within the safety surveillance activities.

7. CONCLUSIONS

Monitoring and observation are fundamental parts for managing the safety of structures. At Ridracoli dam a knowledge support system enables decision support to assist Safety Manager in the surveillance management of the dam. The Mistral system is used as a control panel that shows the current state of the dam and of its structural parts analyzing the evolution of the measured behaviour without time delay. The system obtained very rapid acceptance by the user. It reduced the effort required for the management of warnings and improved the quality of the safety management procedures.