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Information systems for dam safety: evolution through Artificial Intelligence

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Abstract

The paper describes the results of a project which aims at improving the capabilities of an information system that supports the management of dam safety. The improvement has been achieved through additional components developed using artificial intelligence concepts and technologies.

We describe the pre-existing information system, identify users' requirements driving the evolution of the information system and explain how AI concepts and technologies may contribute.

We describe the functions, the architecture and the AI features of two systems (MISTRAL and DAMSAFE) added to the information system.

Finally we give some information about the users' acceptance.

1. The context

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2. The pre-existing information system

[...]

3. User requirements and AI contribution

The limits of the technology described above and the user requirements for its improvement belong to two different levels: local level (management of warnings) and central level (periodical safety evaluation or *deep analysis on demand*).

[...]

4. MISTRAL and DAMSAFE

[...].

4.1. MISTRAL

MISTRAL is a knowledge-based system that supports safety managers when dealing with the interpretation of monitoring data gathered on dams.

MISTRAL receives data from the automatic monitoring system of a dam, identifies the state of the structure and generates natural-language explanations of the results of the evaluation. The result of the evaluation is a set of qualitative indexes, which express the state of the entities which have been assessed (instruments, dam blocks, foundation, physical processes, ...) in terms of values ranging from *normal* to *very high anomaly*❶ .

A man/machine interface allows the user to access the results of the computation. It draws on the screen graphical representations of the objects which have been assessed and displays them using a colour scale based on their state. The interface has been carefully designed to help the users immediately understand the current state of the structure.

MISTRAL provides the users with a 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. The users may also insert comments about the situation whenever they have some additional knowledge which could help understand what is going on.

Since its first conception, MISTRAL's evaluation process has been based on empirical and model-based reasoning: application experts and developers of the system defined heuristics and models of the dam behaviour, which use monitoring data as evidence of the state of the structure. More recently, the idea of using additional information related to specific situations assessed by experts in the past led to the development of a *database* of interesting cases and *tools* to detect possible *analogies* between the situation to be evaluated and those stored in such database. In such a way, MISTRAL provides the users both with its standard evaluation, based on general criteria, and with pointers to past situations which can be regarded as significant to the management of the safety of the structure.

4.1.1. MISTRAL's architecture

MISTRAL comprises the following modules (see **Errore. L'origine riferimento non è stata trovata.**):

- *communication module*: manages the data communication from the monitoring system to MISTRAL;
- *numerical pre-processor*: checks the measurements against thresholds and recognises trends in data;
- *evaluator*: identifies the state of the structure and highlights analogies with past situations;
- *explainer*: generates a natural-language explanation of the deductions carried out by the evaluation module;
- *man/machine interface*: allows the user to access the results of the computation;
- *database management module*: manages an internal 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 MISTRAL was, for some reason, not active.

The numerical pre-processor checks the measurements and their rate of change against thresholds; moreover, it computes the expected values for (some of) the instruments by means of theoretical models and checks against thresholds the displacements of the measured values from the expected ones and their rate of change.

Note that the whole set of thresholds used within MISTRAL has a different meaning from that used by INDACO when the two systems are coupled: while the former are safety thresholds, individuated by safety experts on the ground of their knowledge of the structure and of the past measurements, the latter are purely regarded as instrumental thresholds, used to verify the correct behaviour of the instruments.

Moreover, the numerical pre-processor applies mobile average algorithms to highlight trends in readings of the monitoring instruments.

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❶ Currently, at most five values are used: normal, low anomaly, medium anomaly, high anomaly, very high anomaly; for some objects, only a subset of these values is appropriate.

Two *reasoning agents*, the evaluator and the explainer, process these data and store their results in the internal database, which is used as a *blackboard*: each reasoning agent uses the blackboard to read/write the concepts related to dam safety that it manages.

Essentially, the evaluation is a process of evidential reasoning, which transforms data states into dam states and interprets them in terms of alarm states. Then the explainer maps data and dam states into the proper messages.

The first step of the evaluation synthesises the results of the numerical processor, defining a *qualitative state index* for each instrument, that might range from *normal* to *very high anomaly* (and that, for computational purposes, sometimes is mapped into an integer value); moreover, MISTRAL sets also a parameter to record the *direction* of each measure.

Then the evaluator executes different types of checks on groups of measurements:

1. *checks on sections*: readings from instruments within the same section of the dam are composed (e.g. vertical blocks);
2. *evaluation of physical phenomena*: readings from instruments which measure the same quantity are examined (e.g. displacements, under pressures);
3. *evaluation of physical processes*: readings from instruments which allow the identification of ongoing processes are examined (e.g. rotation of the dam body).

The evaluator acts on a hierarchical model of the dam and uses information chaining techniques in order to establish the current state of the structure starting from local knowledge of the state of the instruments. This is done using several kinds of representations for codifying relationships between the data and the states[8]:

- *numerical functions*: empirical formulas define relations based on the alarm state of single instruments and on their reliability and significance; for instance, the empirical index for a dam block is a linear combination of the state indexes of the instruments belonging to that block, weighted on the ground of the reliability and significance parameters of the instruments. In this way, the most important instruments have a major impact on the definition of the empirical index, whilst alarms from the least reliable instruments may be attenuated or even filtered, when not supported by other ones; therefore, the empirical evaluation acts as an implicit congruency check on groups of data.
- *production rules*: starting from the values of some attributes of the system, rules can be fired, which set other values as well as the activation state of currently ongoing physical processes;
- *constraint based techniques*: constraints among variables define possible states of the system; process identification is driven by the satisfaction of those constraints. An example is shown in Table 1 a rule describes a part of the space state of the process *rotation* of a dam block. If the rule is fired (that is, all the conditions are true), then the activation state of the process is set to the value defined by the conclusion of the rule. In the example, the high downstream displacement of a plumbline installed on a dam block and the high compression of a strain gauge in foundations under the block imply a high downstream rotation process of the dam block.

Moreover, MISTRAL performs pattern recognition on time series: the results of the numerical pre-processor are processed by the evaluator to check relationships between cause and effect quantities (e.g. basin level and displacements) and to explain trends of the time series.

Eventually, MISTRAL applies case-based reasoning by checking the situation under examination against past reference situations, which are regarded as significant in respect of safety management[0]. For this purpose, we have defined a subset of the state indexes, which we consider the most significant ones; MISTRAL applies algorithms and metrics to these parameters to define the degree of similarity between the current situation and those stored in a reference database. Links to the closest-matching cases within the reference database are built on-the-fly and shown to the user through the interface, so that the user can access their evaluations, mainly to take advantage of the additional comments provided by the experts, which might lead the current evaluation.

From the trace of execution, using knowledge about the behaviour of the dam and the instruments, the explanation module generates natural language messages. They describe the current state of the structure and the deductions of the system.

Users can access the processing results through a window-based interface (Figure 2, Figure 3). The interface draws on the screen graphical representations of the objects that have been assessed (instruments, sections) and displays them using a colour scale based on the object's state, by mapping the indexes belonging to the scale *normal - very high anomaly* into colours ranging from green to red, using grey for representing missing information (for instance, malfunctioning instruments).

Figure 2 shows how MISTRAL gives the user information from its interpretation. Small squared lights atop the screen codify the state of the instruments; these squares lie on coloured strips, whose colours represent the state of *families* of instruments of the same type, which are interpreted as the activation states of relevant phenomena, such as movements with reference to plumb lines, deformations with reference to extensometers, seepage with reference to piezometers.

Rectangular lights in the lower part of the screen codify the processes' activation state, such as rotation or translation of a block. The colours of the dam blocks (right shoulder, block 8-10, etc.) and of the strip at the bottom of the screen (global state) summarise the state of the physical system's structural components and the state of the whole structure.

Interactors are available to get more refined information about the dam state, by focusing on interesting details. For instance, when a user presses the grey button 'Block 1-2' in Figure 2, the window shown in Figure 3 appears on the screen: this window presents the current readings recorded by the instruments on the block 1-2 (main section of the dam), a picture of the block, the current state of the instruments (on the right) and of the whole block (on the left) and the explanation of the current state.

Via the interface, the user can also activate functions, such as print screen, and access the internal data bases.

MISTRAL provides users with three data bases, which collect all the data related to the control system, that is measurements, evaluations, explanations and users' comments.

These data bases have different purposes: the first one is dynamically upgraded with the information related to the case under evaluation (historical data base); an other data base stores reference cases to be used by the analogical evaluator (reference data base); the last archive provides the users with test cases, generated through simulation, which show how the system would interpret limit situations (test data base; note that the situations shown here belong to this archive).

Users can select a situation from a data base and see on the screen its graphic representation and explanations. Moreover, several data management functionalities are available to deal with the measurements stored within the data bases, such as statistical functions, export formats, visualisation tools.

4.2. DAMSAFE

DAMSAFE is intended as a *co-operative management tool*, in which different types of information concerning a dam and different types of models of the dam system can be united to assist the engineer in carrying out the procedures of dam safety management (Figure 4).

The system developed so far enables hazard audits to be carried out on descriptions of the state and behaviour of the dam coming from monitoring and from experts' judgement. Moreover, the system interfaces several external data bases. The structure of the system is based on three main entities contained within an integration environment:

1. models of the physical world, which describe both the present state and the desirable or undesirable states of the physical world; they are constructed using object-oriented modelling techniques;
2. models of human reasoning (*reasoning agents*), which are models of reasoning about the problem domain, including identification of data features or mapping of data states into dam states;
3. communication mechanisms, which take the form of interfacing software components, that enable the user to co-operate with the system through an object-oriented man/machine interface.

The whole system can be used in two different ways:

- as a *diagnostic tool*: there is a sequence of operations of the reasoning agents that allows the translation of data into dam states;
- as a *knowledge integrator*: the system facilitates the integration of information about the dam. Drawings, maps and pictures of the dam form part of the information base.

Several databases are linked to the system: a database of past measurements of the dam, a database of laboratory and *in situ* tests and an archive of documents and cadastral information. The system functions as an integration tool for different types of knowledge about the dam, such as theory, regulations and expert knowledge. In this way the system can be seen as a *virtual expert,* that reflects the knowledge of many different experts (civil engineers, hydrologists, geologists,...) interviewed during the knowledge gathering phase.

The structure of DAMSAFE is based on the *object-oriented* approach. Different types of knowledge are integrated using a hierarchical model describing the main components of the system. The hierarchical structure includes two physical *world models* and three *reasoning agents*. The models make up the problem domain, while the reasoning agents contain the knowledge required to reason about the models. They perform a variety of tasks, the most important being that of relating the concepts in the data world to those in the dam world.

4.2.1. Data world and dam world

[...]

4.2.2. Causal net of processes

[...]

4.2.3. Reasoning agents

Three reasoning agents have been developed. The first one (*extractor*) operates solely on the data world to manipulate data and extract features from the data sets. It uses the graphical interface to show to the user a time series plot and to interactively identify *features* of the plot which are considered relevant to dam safety. They are defined by qualitative and quantitative attributes (e.g. spike length, start time) and stored within the data world. These attributes can also be accessed and manipulated through methods of the data world.

The second reasoning agent (*mapper*) performs the task of interpretation identifying the possible behaviours of the dam in terms of a set of processes in the causal net, and the values of various attributes of the dam, based on evidence in the data.

This task is performed by firing *production rules* defined by experts, which link data values to dam states (Table 2). These links are defined by using a formal language designed to allow non-programmers to easily write and read rules (Table 3). When a rule is fired, the state of some dam world process is declared active and some dam world attributes receive a value. The set of active processes linked in a causal chain are highlighted by the system and describe a scenario that demonstrates the evolution of the dam behaviour.

The third reasoning agent (*enforcer*) acts on the dam world to extend the implications of the state identified by the mapper over the model of the dam and its environment. thus highlighting possible causal chains.

4.2.3. On-the-fly creation of objects and interface

A dam's entire information set might be inserted into the system by providing DAMSAFE with a description written in a special language, called ADAM. We have designed ADAM so that users unfamiliar with programming languages can easily build their own data management environment (Table 4).

Through ADAM descriptions users inform the system about the components of the dam currently under evaluation (for instance, blocks) and about the data sources to be linked (for instance, the database of monitoring measurements and its access code).

At run time, DAMSAFE interprets ADAM descriptions and sets up the necessary objects and links to databases, as well as a hypertextual interface based on HTML scripts (HyperText Markup Language). In this way, DAMSAFE can manage links to other databases or procedures (used as reasoning agents) on a net of computers via the hypertext transfer protocol (HTTP).

Furthermore, DAMSAFE translates ADAM descriptions of physical entities, processes of the causal net and links among them into a hierarchy of C++ objects, which are then managed and accessed by the reasoning agents.

5. Status of the implementation and results

[...]

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Figures and Tables

[...]