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Automatic Diagnosis of Anomalous Structural Behaviour

Diagnostic automatique d'un comportement structural anormal

Automatische Diagnose anomalen Tragwerkverhaltens

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SUMMARY

The article describes the features of the installed monitoring system and analyses the different methods employed to validate the measurements carried out and to define the 'confidence thresholds'. Moreover, it presents the 'physiological' behaviour in time of some monuments and the first decisional guidelines for the diagnosis of the risk.

RÉSUMÉ

L'article décrit les caractéristiques d'un système de surveillance installé et analyse les différentes méthodes employées afin de valider les mesures effectuées et de déterminer les seuils de confiance. Il décrit le comportement physiologique de certains monuments et présente des directives pour établir une évaluation du risque.

ZUSAMMENFASSUNG

Nach einer kurzen Beschreibung der Eigenschaften der installierten Kontrollsysteme werden im Artikel die verschiedenen angewandten Methoden dargestellt, um die Messergebnisse zu validieren und Vertrauensbereiche zu definieren. Ausserdem werden die physiologischen Verhaltensweisen einiger Denkmäler im Laufe der Zeit sowie die ersten Entscheidungsrichtlinien für die Diagnose des Risikos beschrieben.

1. FOREWORD

On March 17, 1989 the Civic Tower of Pavia collapsed; this collapse took away one of the most representative monuments of the town. After this event, the Ministry of Civil Defence appointed a technical-scientific Committee to analyze the causes of the tower collapse and to determine the state of other monuments of the town.

The Committee activity, performed on behalf of the Public-Works Office of "Regione Lombardia", includes a wide and complex plan of monitoring surveys and interventions to be carried out on the Cathedral and on six town towers.

This article describes the experience gained in the historical monuments of Pavia; data collected by a complex monitoring system have been systematically processed and critically interpreted in order to define limits and alert thresholds on different measurement channels as to investigate the structure behaviours providing some interpretation criteria in order to realize an automatic system for risk diagnosis.

2. THE AUTOMATIC MONITORING SYSTEM

In order to control the Cathedral and the six Towers, a sophisticated automatic monitoring system based on eight Peripheral Measurement Units and one Data Acquisition Centre have been installed in 1990. The peripheral measurement units, installed inside the monuments to be monitored, are linked via radio with the centre, located at the University of Pavia. Fig.1 shows the block diagram of the system and the list of the instruments installed an each monument [2].

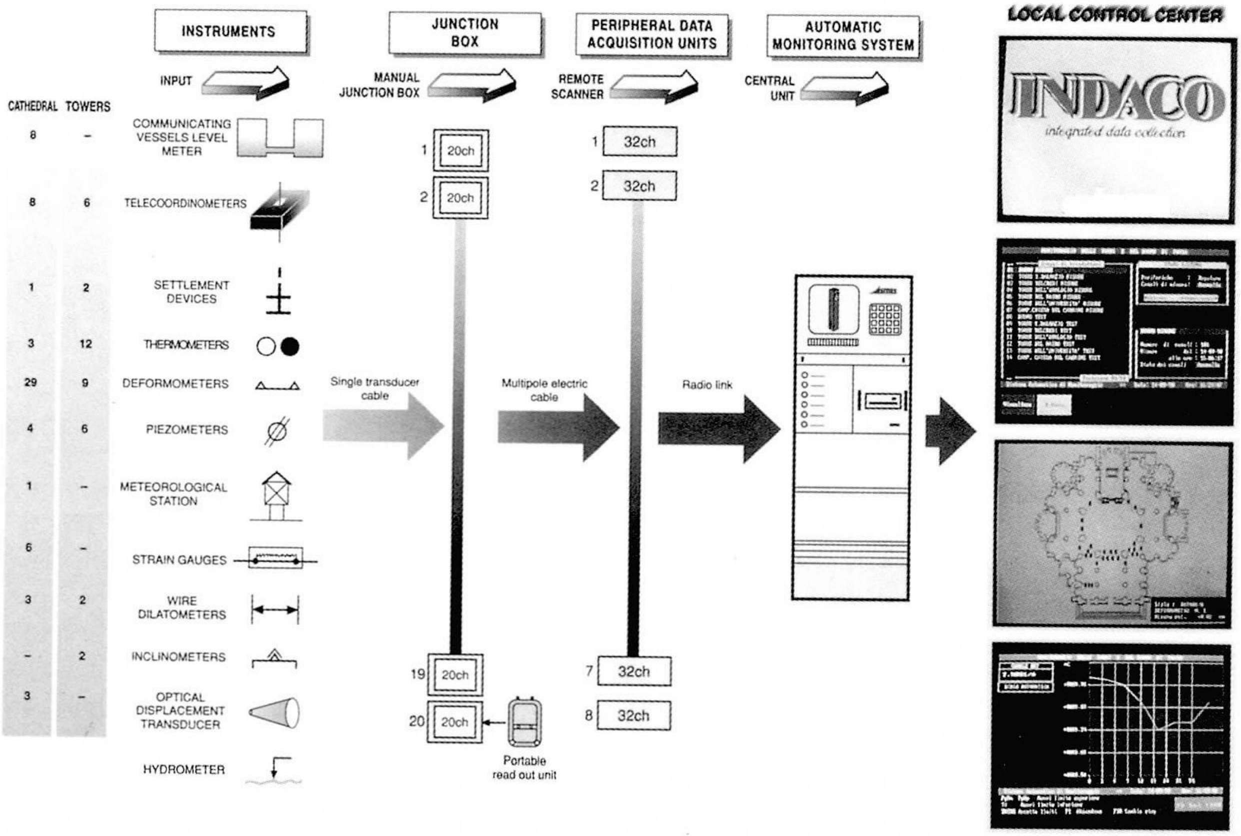

Figure 1: Pavia Towers and Cathedral. Data acquisition system: block diagram

The installed instrumentation allows to acquire the most important "cause" and "effect" variables on each monument. In particular the monitoring activity concerns:

- opening-closure of significant cracks in the Cathedral and on the towers, measured by automatic deformometers;
- global displacements of the structures, considering the displacement of the Cathedral dome and the displacement of the top of the towers, measured by plumb-lines and automatic telecoordinometers;
- planimetric displacements of the Cathedral dome, measured by automatic optical sights;
- foundation settlements of the columns of the Cathedral dome, measured by a level measuring circuit of communicating vessels;
- stress on the chains installed between two pillars of the Cathedral, measured by strain gauges;
- cross strains of some tower walls and of one Cathedral column, measured by wire dilatometers;
- "cause" variables such as air and masonry temperature, solar radiation, wind, groundwater level, measured by means of meteo-units, piezometers, thermometers placed inside the walls.

3. MEASURES MANAGEMENT

Measures automatically gathered by the monitoring system have been periodically transferred into the historical data bank managed by MIDAS code [4], installed on ISMES computers in Bergamo. Measures acquisition, storage and processing, carried out for about three years, have allowed to set-up a data base which can be used for graphic tables representing chronological measurement diagrams and results of processing and correlations among these magnitudes. This data base was also used to analyze the acquired measures and to evaluate the thresholds values for the on-line control.

4. ON-LINE CONTROL

The automatic monitoring system installed on the Cathedral and on the Towers is provided with special package (INDACO), developed by ISMES, able to evaluate the reliability of the acquired measures and to identify any anomaly.

These anomalies can be caused either by instrument failure or by really "anomalous" situations in the structure behaviour; it is therefore important to determine which problem is actually present.

Different criteria have been determined to identify different situations. Each read value is subjected to a validation and control procedure carried out on the automatic monitoring system. The architecture of the control is showed in Fig. 2.

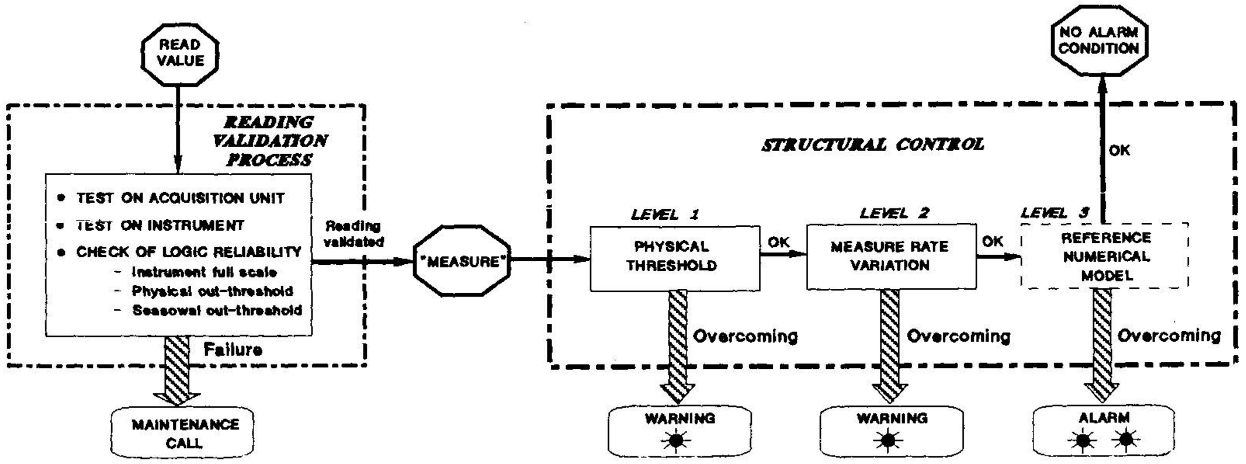

Figure 2: On line control architecture

The instrument measures are deeply investigated and checked, thus excluding any instrument fault: the "reading validation process". After these controls each acquired value is compared with preset and various ranges ("thresholds") for the "structural control". Measures inside these ranges are first of all reliable and then detect a normal behaviour of the structure under control. The measures are validated according to the past behaviour of the structure by means of two different control levels:

- the first level consists in the control of a physical threshold in order to verify that the measure falls within a variation range defined according to the physical characteristics of the quantities under examination or to the past evolution of the measures. This variation interval is determined either through a minimum and a maximum value ("fixed" thresholds) or through a tolerance interval connected with a periodic variation of measures ("periodic" thresholds).

- the second level consists in the control of the variation rate of the measures. This speed shall not overcome a preset threshold, determined, even in this case, according to the values obtained with the measures taken in the past. This control is carried out only after the successful of the first level controls.
  The characteristic parameters of the "fixed" thresholds are minimum and maximum values calculated according to measures average and standard deviation.
  While measures showing periodic variation are interpolated with a "periodic" function through a Fourier series development.

A third level control is the comparison between real measures and measures provided by reference numerical models based on the real behaviour of the structure. This has not been installed on line but it is activated off line by forecasting automatic procedures of the MIDAS code, after the measure has been stored in the historical data base.

The validation criteria are the same for all sensors installed for "cause" and "effect" magnitudes too.

Figure 3a shows the opening-closure history of a crack (solid line), read in the dome of the Cathedral, together with the established threshold bounding values (dotted lines). Figure 3b gives the same information on the opening-closure variation rate: the dotted line is the maximum threshold value.

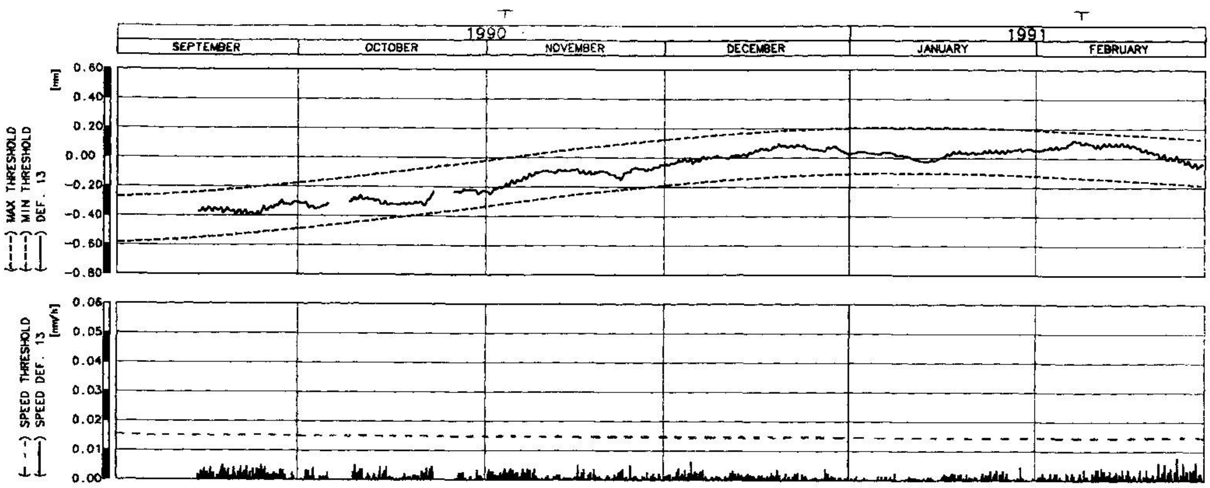

Figure 3: An example of periodic threshold of the measures.

5. EXPERT SYSTEMS AS EVOLUTION OF THE ON LINE CONTROL

The software developed for checking the performance of the Pavia monuments is able to alert in real time on the presence of readings in disagreement with the established thresholds. It should be considered that the information provided consist of different types of signals, which are related to a given time and in principle may not be easily correlated within a consistent physical process.
The risks correlated to such a situation are twofold. On one hand, the surveillance personnel cannot judge about the potential risk associated to the anomalous readings; specifically they cannot differentiate accidental conditions from indicators of a risk event.
On the other hand, the correlation of the measures and the evaluation of the actual impact of the different 'on-line' readings may require delays not compatible with the safety needs. This consideration holds when brittle structural collapse is included in the risk scenarios, as in the case treated in this paper.
The introduction of an expert System, capable of synthetizing the readings received with consistent structural interpretative models is the natural evolution of the on-line monitoring network. Being based on artificial intelligence techniques, the mandatory step towards the development of an expert system is the robust understanding of the structural behaviours possibly occurring in the operational life of the monitoring network. In section 6 the indications emerged from the study of the possible structural behaviours of the Pavia monuments are described. They are used as guiding indicators in the design of the expert system, whose main characteristics are summarized in section 7.

6. BEHAVIOUR ANALYSIS

Measures acquired by the automatic monitoring system allow to analyze the structural behaviour of the monuments and to evaluate their safety state.

The global displacements of the structures and the local deformation phenomena, especially for the Cathedral because of its complexity, were determined by an interpretative analysis of the measures, particularly referring to the most important structural parts (dome, drum and piers), considering horizontal displacements of the dome columns, displacements of the top of the dome, differential settlements of the columns bases and opening-closing cycles of the main cracks.

Planimetric displacements of the dome columns, measured by the telecoordinometers, mainly occur in radial direction with different values from column to column (the magnitude is about one millimeter). A strong correlation with air temperature variations has been evidenced. The measures acquired by the monitoring system have also allowed to point out daily phenomena, of the order of 0.1 millimeter. The different displacement amplitudes, both seasonal and daily, are due to the different structural stiffness and to the different insolation (greater amplitudes for columns placed on the South side of the structure).

Displacements measured at the dome top by optical sights have a components depending on temperature seasonal variations (Figure 4).

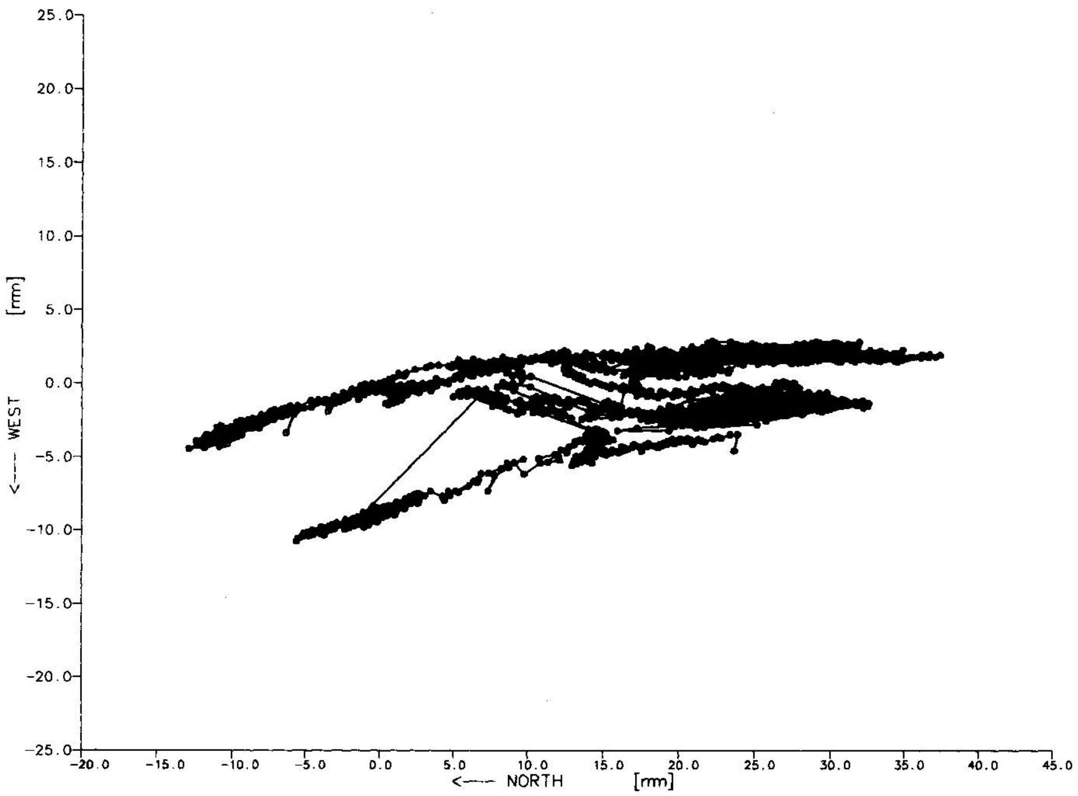

Figure 4: Planimetric displacements of the Cathedral dome

There is a logic correlation between piers horizontal displacements and vertical displacements of the dome top: in summer piers move outwards the octagon while the dome top lowers; on the contrary, in winter piers move inwards the octagon and the dome top lifts.

Cracks show periodic patterns according to the seasonal variation of the temperature, with different amplitudes: greater values are usually recorded by instruments placed on cracks near the nave arch between two dome columns.
Generally deformometers installed on cracks have provided values indicating regular stability, thus excluding drift phenomena.

7. RISK DIAGNOSIS

The behaviour analysis carried out on the Cathedral and on the Towers has pointed out the presence of particular cyclic phenomena with seasonal and daily period mainly linked to temperature variations. This analysis has also allowed to check the logical consistency between the information provided by different instruments (telecoordinometers on piers, optic sights on the dome top, strain gauges on cracks) concerned with the same phenomena.

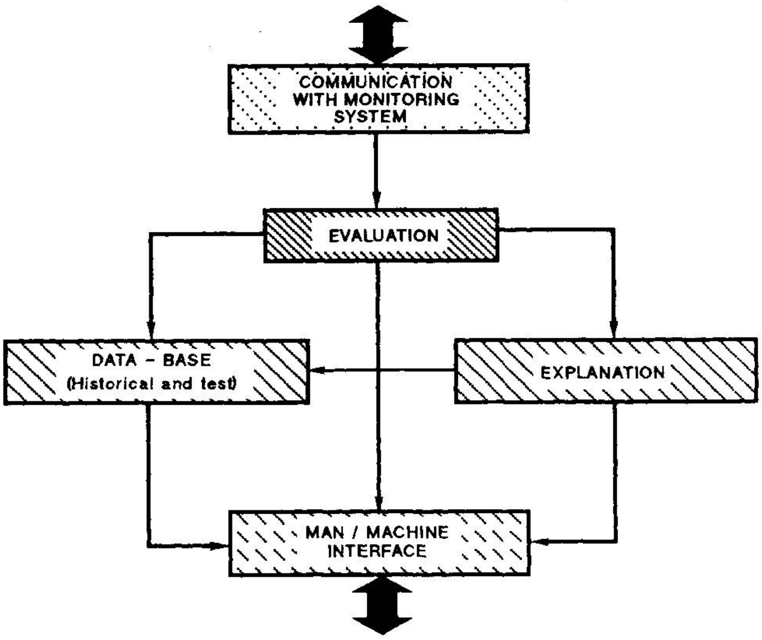

Figure 5: MISTRAL Architecture

These typical connections, both from a qualitative and quantitative point of view, have been introduced in MISTRAL expert system, developed by ISMES to manage and interpret signals coming from automatic monitoring systems installed on important structures. This system is already working for the on line behaviour evaluation of some dams.

Now applied for the first time on a monumental structure, it is experiented on the Pavia Cathedral with off line test. It completes the on line control procedure as showed in Fig. 5.

It allows to filter alarms coming from the automatic monitoring system, by intercepting signals due to accidental overcoming of the control thresholds, providing an explanation to its assumptions and an evaluation of the structural behaviour. This system, therefore, carries out in real time a part of the evaluations of the safety state of the structure, which are usually made off line by experts in safety problems.

From an engineering point of view, the expert system checks homogeneity, priority and congruence of each result of the on-line controls, according to reference structural behaviours. Each control is taken into account also considering the correctness of the installed instruments and their intrinsic and statistic reliability.

According to engineering considerations, it has been possible to determine measures groups concerned with the same process and physical phenomena interesting the structure. The control of the congruence relations allows to

determine the real state of each single measure group under consideration; from the local condition of the different groups it is possible to define the overall structure condition, according to considerations linked to experience and engineering evaluation.
MISTRAL expert system, filtering and classifying anomalies of each elementary control by comparison with reference structural behaviours, can point out the presence of real critical situations and generate alarm signals only for those conditions really interesting Control Experts. This expert system is therefore another instrument for Responsible for "surveillance", helping them to carry out their activity more timely and effectively.

8. CONCLUSION

The engineering knowledge and the learning of the structural behaviour of great modern civil buildings has increased drastically in the last years and has reached a very high level. A similar knowledge must be still developed for the historical monuments in order to define general criteria of the automatic surveillance using on line control systems. The problem involves great and objective difficulties; very soon there aren't geometric drawings, structures are complex and different from each other and building materials are often not known.
ISMES has gatered a great experience about historical monuments, both in the monitoring system installation and managing and in numerical mathematical modelling. Some very important examples are: Brunelleschi Dome in Florence , S. Marco Cathedral in Venice, Milano Cathedral, Loggia della Signoria in Florence, Atri Cathedral, Arezzo Cathedral and Pisa tower (as associated of "Consorzio Progetto Torre di Pisa"). These experiences has allowed to improve the technics and methods used in data analysis. Therefore the use of an expert system for the Pavia cathedral control is the result of an evolutive process.
If this project will provide positive results the expert system could become an important help instrument in solving problems related to preservation of the precious artistic Italian heritage and in preventing catastrophic accidents, such as in Pavia, from taking place.

REFERENCES

1. MAURIZIO VAVASSORI - "Un progetto per sette monumenti a rischio " Rassegna della protezione Civile Maggio 1990

2. F. ERRICHIELLO, G. MACCHI, M. VAVASSORI - "Monitoraggio strutturale delle Torri e del Duomo di Pavia: un sistema per il controllo in linea della stabilita' dei monumenti" - AIPND Milano 1990

3. P. ROSSI,M. VAVASSORI - "Il monitoraggio di edifici monumentali. Le torri ed il Duomo di Pavia" - RECUPERO EDILIZIO Centro studi "OIKOS" - Ente fiere SAIE Bologna Ottobre 1992

4. ISMES - MATHEMATICAL MODELS DEPARTMENT - "MIDAS: Management of information for Dam Safety"

5. S. LANCINI, M. LAZZARI, A. MASERA, R. MENGA, P. SALVANESCHI - "MISTRAL - An expert system for the management of warnings from automatic monitoring systems of dams (in italian) - Internal report ISMES BG 1992

6. A. CASTOLDI, F. ANESA, L. IMPERATO, F. GAMBA - CATTEDRALE DI S. MARIA DEL FIORE, FIRENZE : Sistema di monitoraggio strutturale della Cupola e del suo basamento - Quaderno ISMES n. 212