Monitoring Distributed Parameter Systems
Based on Expert Systems and Sensor Networks

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Abstract: - The paper presents an application of expert systems for monitoring phenomenon seen as distributed parameter systems. The information from these systems may be obtained using sensor networks and estimation techniques. The problem is formulated in the frame of general knowledge about distributed parameter systems, with application at the heat transfer. A knowledge base may be developed using human expertise on such distributed parameter system, related to the way how the phenomenon is happenning in time and space. The expert system may be implemented in real time using virtual instrumentation. The resulted virtual instrument can be placed in the real distributed parameter system, as a tool for fault detection and diagnosis.

Keywords: - Wireless sensor networks, expert systems, distributed parameter systems, fault detection and diagnosis.

1 Introduction
Advances in scientific computation and developments in spatial sensor technology have enhanced the ability to develop modelling strategies and experimental techniques for the study of the space-temporal response of distributed parameter systems. Identification algorithms [3, 10] based on detailed space and time experimental data have an important role in practical applications. Wireless automation is today an emerging topic. In the survey paper for system identification [4] it is shown that the sensor networks [2] represent “an open area in system identification, being a rapidly evolving technology to collect information with many spatial distributed, autonomous devices. They have an interesting potential for industrial monitoring purposes [5] and adds to the richness of information for model development.” The main principles consists in the fact that in this kind of identification the sensor network may be seen as a “distributed sensor” placed into a field, which is a distributed parameter system, allowing measurement in well-chosen points of an infinite variable system.

The developing of an expert system needs a “subject-matter expert”, as an expert in the domain of the process seen as a distributed parameter system, for example, an expert in the field of the heat transfer in space, or in the wave propagation and so on. The human expert must know how the phenomenon happenings in space and in time. In the last years many papers were published in the field of expert systems with different applications [1, 6, 8, 9].

The novel contribution of this paper consists in applying some multiple concepts as: sensor networks for measurement, multivariable estimation techniques, virtual instrumentation for implementation and expert systems for analysis, to distributed parameter systems, for system monitoring, fault detection and diagnosis, as it is illustrated in Fig. 1.

Fig. 1. Research domains involved in application

An example how to extract the knowledge from the phenomenon happening in distributed parameter systems and convert it into a form suitable for human external monitoring is presented. The status of the
A rule base is developed and at each moment different rules may be activated. In the first stage the expert system is developed with simple true/false logic. But, in a next stage it may perform also complex evaluation based on fuzzy logic, for example. The expert system may be implemented, in real time, in the block diagram of a virtual instrument, using pre-defined virtual instruments from the LabView toolboxes. The control panel of the virtual instrument provides a user friendly interface, with graphical representations. The fault detection and diagnosis in this application may be framed in the area of “machine diagnostics”. The current state of the distributed parameter system may be determined using measurements from the sensor but also estimations.

2. Knowledge about a phenomenon seen as a distributed parameter system

Many physical phenomenon happening in time in space may be seen as distributed parameter systems, with time and space variables, described with partial differential equations. Some examples of distributed parameter systems are: propagation of sound or heat, electrostatics, electrodynamics, fluid flow, elasticity. These are distinct physical phenomena but they have identical mathematical formulations, and the same underlying dynamics govern them [8].

From these examples a very practical process is the heat transfer in space, which is chosen for study in this paper. The temperature in space may be measured using temperature sensors from a wireless sensor network. Let it be \( \theta(P,t) \) the function of and object’s temperature, at the time moment \( t \), where \( P \) is a point in the object’s volume. If different points of object have different temperatures, \( \theta(P, t)\neq ct. \), then a heat transfer will take place, from the warmer parts to the less warm parts. The law of heat propagation through an object with a heat source is:

\[
\rho \frac{\partial \theta}{\partial t} = \text{div}(k \text{ grad } \theta) + F(t, P)
\]  

(1)

where \( k \) is a proportionality factor, called coefficient of internal thermal conductivity of the object, and \( a = \sqrt{k/\gamma \rho} = ct. \) if the object is homogenous and \( F \) is the heat source distribution in the object [8]. We must take in consideration the initial state of the object, the temperature distribution in the object at the moment \( t=0 \), the initial conditions:

\[
\theta(x, y, z, 0) = f(x, y, z)
\]  

(2)

An example of temperature variation, for a heat transfer from a source, is presented in Fig. 2.

Fig. 2. Temperature variation

So, the points from the space in which the phenomenon is happening are denoted \( P_i \), with the coordinate \( z_i \). For a bidimensional space in a system coordinate \( xOy \), \( z_i=(x_i, y_i) \). The phenomenon as distributed system is monitored with a sensor network with \( n \) sensors \( S_i, \ i=1,\ldots,n \), placed in \( n \) points \( P_i \) from the space, like in Fig. 3.

Fig. 3. Space monitoring scheme

For a reduced number of sensors a recommended placement map of these sensors in plane is presented in Fig. 4. This map is obtained according to the optimized mesh and node positions for an accurate solving of the partial derivative equation of heat transfer (1).
Knowledge that may be determinate from measurements upon the process variables made using sensor networks is as follows:

-the value $v_i$ of the phenomenon at a time moment, in a point of the space $P_i$, which is the value provided by the sensor $S_i$, placed in the point $P_i$, at the time moment $t$: $\vartheta_i(t)$, temperature in this case;

-the speed of the phenomenon $s_i$, which is the derivative in time of the variables measured by sensor $S_i$ in the point $P_i$, at two consecutive time moments $t$ and $t-h$:

$$\frac{d\vartheta_i(t)}{dt} \approx \frac{\vartheta_i(t) - \vartheta_i(t-h)}{h},$$

where the discrete time approximation is used, for a constant sample period $h$;

-the value of the difference in space $d_i$, from two adjacent sensor variables: $d\vartheta_i(t) = \vartheta_i(t) - \vartheta_j(t)$, given by the sensors $S_i$ and $S_j$, placed in the points $P_i$ and $P_j$; The difference in space is given the sense in which the phenomenon is happening. The positive sense is considering from $S_i$ to $S_j$. This difference is proportional to the space between two sensors $S_i$ and $S_j$, or points $P_i$ and $P_j$, $|z_i - z_j|$, where $z_i$ and $z_j$ are the space coordinates of the two points. For a bidimensional space the coordinates are for $P_i(x_i,y_i)$ and $P_j(x_j,y_j)$.

-the speed $s_{ij}$ of difference variation between two adjacent sensors $S_i$ and $S_j$, placed in the points $P_i$ and $P_j$, as time derivative of space difference:

$$d\Delta \vartheta_i(t) \approx \frac{\Delta \vartheta_i(t) - \Delta \vartheta_i(t-h)}{h},$$

at two consecutive time moments $t$ and $t-h$. The speed of the difference in space is given the speed of the space displacement in a sense in which the phenomenon is happening.

We may use also the variables obtained as estimation, as it follows.

-the estimated value $\hat{v}_i$ of the phenomenon at a time moment, in a point of the space $P_i$, which is the value provided by the estimator $E_i$, for the point $P_i$, at the time moment $t$: $\hat{\vartheta}_i(t)$;

-the speed of the estimated phenomenon $s_i$, which is the derivative in time of the estimated variables provided by the estimator $E_i$, for the point $P_i$, at two consecutive time moments $t$ and $t-h$:

$$\frac{d\hat{\vartheta}_i(t)}{dt} \approx \frac{\hat{\vartheta}_i(t) - \hat{\vartheta}_i(t-h)}{h},$$

where the discrete time approximation is used, for a constant sample period $h$;

-the estimated difference in space $\hat{d}_{ij}$, from two values of two adjacent sensor variables: $\Delta \hat{\vartheta}_{ij}(t) = \hat{\vartheta}_i(t) - \hat{\vartheta}_j(t)$, given by the estimators $E_i$ and $E_j$, for the points $P_i$ and $P_j$; The estimated difference in space is given the estimated sense in which the phenomenon is estimated to take place.

-the estimated speed $\hat{s}_{ij}$ of the estimated difference variation between two estimators $E_i$ and $E_j$, for two adjacent points $P_i$ and $P_j$, as time derivative of estimated space difference:

$$d\Delta \hat{\vartheta}_{ij}(t) \approx \frac{\Delta \hat{\vartheta}_{ij}(t) - \Delta \hat{\vartheta}_{ij}(t-h)}{h},$$

at two consecutive time moments $t$ and $t-h$. The speed of the difference of estimates in space is given the speed of the estimate of the space displacement in a sense in which the phenomenon is estimated to happen.

Some errors between the estimates and the actual variables may be introduced: $e_v = v - \hat{v}$ - the error at the process value; $e_s = s - \hat{s}$ - the error in speed of phenomenon happening in some field point; $e_d = d - \hat{d}$ - the error in space difference of two adjacent points and $e_{sd} = sd - \hat{sd}$ - the error of speed of phenomenon propagation in space.

To make estimation we may use the values provided by the sensors. So, two estimation algorithms may be used [10].

**Estimation algorithm 1.** It estimates the value of the variable $\hat{\vartheta}_{i+1}$ at the moment $t_{k+1}$, measuring the
values of the variables $\theta_{k+1}^i, \theta_{k+1}^j, \theta_{k+1}^l$ at the antecedent time moment $t_k$:

$$0_{k+1}^i = f_i(\theta_{k+1}^i, \theta_{k+1}^j, \theta_{k+1}^l)$$  (3)

This is a multivariable estimation algorithm, based on the adjacent point in space (nodes or sensors).

Estimation algorithm 2. It estimates the value of the variable $\theta_{k+1}^i$ at the moment $t_{k+1}$, measuring the values of the same variable $\theta_{k-1}, \theta_{k-1}^j, \theta_{k-2}^j, \theta_{k-3}^j$, but at four anterior moments $t_k, t_{k-1}, t_{k-2}$ and $t_{k-3}$.

$$0_{k+1}^i = f_j(\theta_{k-1}, \theta_{k-1}^j, \theta_{k-2}^j, \theta_{k-3}^j)$$  (4)

The estimator could be a linear or a non-linear one, described by the function $y = f(u_1, u_2, ..., u_n)$, using different estimator methods. In different previous papers different estimators were tested and compared: a linear estimator, an estimator based on a feedforward neural networks with continuous values and an estimator based on an ANFIS [10].

3. Detection strategy based on expert system

For these process variables $v, s, d, sd$ and for the estimated variables $\hat{v}, \hat{s}, \hat{d}, \hat{sd}$ some values may be defined as negative N and positive P or around zero Z, with some degrees: small S, medium M or big B. So we may have the following combinations put on an axis: NB, NM, NS, Z, PS, PM, PB. To emphasize a non-linear character of the process the usage of only three fuzzy values is recommended.

The reasoning is as follows: -If the derivatives are negative we may say the phenomenon is decreasing. -If the derivative is positive the phenomenon is increasing; -If the differences are negative the phenomenon sense is opposite from the two sensors and measuring points. -If the speed of the difference is positive the space becomes to be not homogenous, something is happening in the space between the two sensors.

The expert system is developed using a “backward chaining”. Some rules from the rule base for this expert system are: (1) IF $v$ is Z THEN the process is supressed ($c_f = 10 \%$); (2) IF $v$ is NOT Z THEN the process is supressed ($c_f = 90 \%$); (3) IF $s$ is Z THEN the process is NOT in course ($c_f = 10 \%$); (4) IF $s$ is NOT Z THEN the process is in course ($c_f = 90 \%$) and so on. Many other rules may be developed according to the considerations made above.

The application may be framed in so called “goal driven methods”. In the real distributed parameter systems there are phenomenon with small certainty and their opposite seems to be true. When an expert system is developed for monitoring distributed parameter systems it is necessary to test both, to see what it is happening in the field.

The detection structure uses the time series of measured data provided by each sensor and relies on a regressive multivariable predictor placed in base stations as it is presented in Fig. 4.

![Fig. 5. Detection structure](image)

The values provided by the sensors and the estimated values obtained from the estimator are used by the expert system to obtain decisions.

4. Application

A Crossbow sensor network including a base station and sensor nodes was used in practice. The base station is an IRIS module, a gateway MIB250, which is connected at the USB. The sensor nodes have a processor/radio module IRIS, which are activating the measuring system of small power. They are working at the frequency of 2,4 GHz. The sensor circuit MTS400 includes a temperature sensor. The sensor network has also the software MoteView, for data acquisition, which is reading data from a database PostgreSQL.

Virtual instrumentation, based on National Instruments technology, was used for sensor network monitoring. A virtual instrument for sensor network monitoring was built on a personal computer [11]. It includes: data acquisition and processing, estimator, data base, results table and an Excel data base. The control panel is presented in Fig. 6.
5 Conclusion
An application expert systems for monitoring distributed parameter systems, with exemplification at the process of heat transfer is presented. The knowledge on distributed parameter system, the measured variables acquired from the system using a sensor network and some estimates obtained with estimation techniques are used. The expert system may be implemented on a virtual instrument. It offers a graphical user interface. Applications of this solution are in the field of fault detection and diagnosis and malicious node detection.

References: