IN PARTNERSHIP WITH:
Institut français des sciences et technologies des transports, de l'aménagement et des réseaux - IFSTTAR

Activity Report 2015

Project-Team I4S

Statistical Inference for Structural Health Monitoring

RESEARCH CENTER
Rennes - Bretagne-Atlantique

THEME
Optimization and control of dynamic systems

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Creation of the Team: 2009 April 01, updated into Project-Team: 2013 January 01

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2. Overall Objectives

2.1. Overall Objectives

monitoring, system identification, on-line identification and detection algorithms, statistical hypotheses testing, reflectometry, infrared thermography, non destructive testing, sensors fusion, optimal sensors placement, vibration-based structural analysis and damage detection and localization, aeronautics, civil engineering

2.1.1. In Summary

The objective of this team is the development of Structural Health Monitoring techniques by intrinsic coupling of statistics and thermo-aeroelastic mixing modeling for the development of robust and autonomous structural health monitoring solutions of mechanical structures. The emphasis of the team is the handling of very large systems such as the recent wind energy converters currently being installed in Europe, building on the expertise acquired by the team on bridges as an example of civil engineering structure, and for aircrafts and helicopters in the context of aero elastic instability monitoring. The necessity of system identification and damage detection systems robust to environmental variations and being designed to handle a very large model dimension motivates us. As examples, the explosion in the installed number of sensors and the robustness to temperature variation will be the main focus of the team. This implies new statistical and numerical technologies as well as improvements on the modeling of the underlying physical models. Many techniques and methods originate from the mechanical community and thus exhibit a very deep understanding of the underlying physics and mechanical behavior of the structure. On the other side, system identification techniques developed within the control community are more related to data modeling and take into account the underlying random nature of measurement noise. Bringing these two communities together is the objective of this joint team between Inria and IFSTTAR. It will results hopefully in methods numerically robust, statistically efficient and also mixing modeling of both the uncertainties related to the data and the associated complex physical models related to the laws of physics and finite element models.

Damage detection in civil structures has been a main focus over the last decade. Still, those techniques need to be matured to be operable and installed on structures in operation, and thus be robust to environmental nuisances. Then, damage localization, quantification and prognosis should be in that order addressed by the team. To be precise and efficient, it requires correct mixing between signal processing, statistical analysis, Finite Elements Models (FEM) updating and a yet to be available precise modeling of the environmental effects such as temperature through 3D field reconstruction.

Theoretical and practical questions are more and more complex. For example, in civil engineering, from handling hundreds of sensors automatically during some long period of time to localize and quantify damage with or without numerical models. Very large heavily instrumented structures are yet to come and they will ask for a paradigm in how we treat them from a renewed point of view. As the structures become large and complex, also the thermal and aeroelastic (among others) models become complex. Bridges and aircrafts are the main focus of our research. Opening our expertise on new applications topics such as helicopters and wind energy converters is also part of our priorities.

2.1.1.1. Objectives

The main objectives of the team are first to pursue current algorithmic research activities, in order to accommodate still-to-be-developed complex physical models. More precisely, we want successively

- To develop statistical algorithms robust to noise and variation in the environment
- To handle transient and highly varying systems under operational conditions
- To consider the impact of uncertainties on the current available identification algorithms and develop efficient, robust and fast implementation of such quantities
- To consider relevant non trivial thermal models for usage in rejection based structural health monitoring and more generally to mix numerical model, physical modeling and data
- To develop theoretical and software tools for monitoring and localization of damages on civil structures or instability for aircrafts
- To explore new paradigms for handling very large and complex structures heavily instrumented (distributed computing)
- To study the characteristics of the monitored mechanic structures in terms of electromagnetic propagation, in order to develop monitoring methods based on electrical instrumentations.
- To consider society concerns (damage quantification and remaining life prognosis)

2.1.2. Introduction to physics driven dynamical models in the context of civil engineering elastic structures

The design and maintenance of flexible structures subject to noise and vibrations is an important topic in civil and mechanical engineering. It is an important component of comfort (cars and buildings) and contributes significantly to the safety related aspects of design and maintenance (aircrafts, aerospace vehicles and payloads, long-span bridges, high-rise towers...). Requirements from these application areas are numerous and demanding.

Detailed physical models derived from first principles are developed as part of system design. These models involve the dynamics of vibrations, sometimes complemented by other physical aspects (fluid-structure interaction, aerodynamics, thermodynamics).

Laboratory and in-operation tests are performed on mock-up or real structures, in order to get so-called modal models, ie to extract the modes and damping factors (these correspond to system poles), the mode shapes (corresponding eigenvectors), and loads. These results are used for updating the design model for a better fit to data, and sometimes for certification purposes (e.g. in flight domain opening for new aircrafts, reception for large bridges).

The monitoring of structures is an important activity for the system maintenance and health assessment. This is particularly important for civil structures. Damaged structures would typically exhibit often very small changes in their stiffness due to the occurrence of cracks, loss of prestressing or post tensioning, chemical reactions, evolution of the bearing behavior and most importantly scour. A key difficulty is that such system characteristics are also sensitive to environmental conditions, such as temperature effects (for civil structures), or external loads (for aircrafts). In fact these environmental effects usually dominate the effect of damage. This is why, for very critical structures such as aircrafts, detailed active inspection of the structures is performed as part of the maintenance. Of course, whenever modal information is used to localize a damage, the localization of a damage should be expressed in terms of the physical model, not in terms of the modal model used in system identification. Consequently, the following elements are encountered and must be jointly dealt with when addressing these applications: design models from the system physics, modal models used in structural identification, and, of course, data from sensors. Corresponding characteristics are given now: Design models are Finite Element models, sometimes with tens or hundreds of thousands elements, depending on professional habits which may vary from one sector to another. These models are linear if only small vibrations are considered; still, these models can be large if medium-frequency spectrum of the load is significant. In addition, nonlinearities enter as soon as large vibrations or other physical effects (aerodynamics, thermodynamics, ..) are considered. Moreover stress-strain paths and therefore the response (and load) history comes into play.

Sensors can range from a handful of accelerometers or strain gauges, to thousands of them, if NEMS (Nano Electro Mechanical Structures), MEMS (Microelectromechanical systems) or optical fiber sensors are used. Moreover, the sensor output can be a two-dimensional matrix if electro magnet (IR (infrared), SAR, shearography ...) or other imaging technologies are used.

2.1.2.1. Multi-fold thermal effects

The temperature constitutes an often dominant load because it can generate a deflection as important as that due to the self-weight of a bridge. In addition, it sometimes provokes abrupt slips of bridge spans on their bearing devices, which can generate significant transient stresses as well as a permanent deformation, thus contributing to fatigue.

But it is also well-known that the dynamic behavior of structures under monitoring can vary under the influence of several factors, including the temperature variations, because they modify the stiffness and thus the modes of vibration. As a matter of fact, depending on the boundary conditions of the structure, possibly uniform thermal variations can cause very important variations of the spectrum of the structure, up to 10%, because in particular of additional prestressing, not forgetting pre strain, but also because of the temperature dependence of the characteristics of materials. As an example, the stiffness of elastomeric bearing devices vary considerably in the range of extreme temperatures in some countries. Moreover, eigenfrequencies and modal shapes do not depend monotonically with temperature. Abrupt dynamical behavior may show up due to a change of boundary conditions e.g. due to limited expansion or frost bearing devices. The temperature can actually modify the number of contact points between the piles and the main span of the bridge. Thus the environmental effects can be several orders of magnitude more important than the effect of true structural damages. It will be noted that certain direct methods aiming at detecting local curvature variations stumble on the dominating impact of the thermal gradients. In the same way, the robustness and effectiveness of model-based structural control would suffer from any unidentified modification of the vibratory behavior of the structure of interest. Consequently, it is mandatory to cure dynamic sensor outputs from thermal effects before signal processing can help with a diagnostics on the structure itself, otherwise the possibility of reliable ambient vibration monitoring of civil structures remains questionable. Despite the paramount interest this question deserves, thermal elimination still appears to challenge the SHM community.

2.1.2.2. Toward a multidisciplinary approach

Unlike previously mentioned blind approaches, successful endeavours to eliminate the temperature from subspace-based damage detection algorithms prove the relevance of relying on predictive thermo-mechanical models yielding the prestress state and associated strains due to temperature variations. As part of the CONSTRUCTIF project supported by the Action Concertée Incitative Sécurité Informatique of the French Ministry for Education and Research, very encouraging results in this direction were obtained and published. they were substantiated by laboratory experiments of academic type on a simple beam subjected to a known uniform temperature. Considering the international pressure toward reliable methods for thermal elimination, these preliminary results pave the ground to a new SHM paradigm. Moreover, for one-dimensional problems, it was shown that real time temperature identification based on optimal control theory is possible provided the norm of the reconstructed heat flux is properly chosen. Finally, thermo-mechanical models of vibrating thin structures subject to thermal prestress, prestrain, geometric imperfection and damping have been extensively revisited. This project led by Inria involved IFSTTAR where the experiments were carried out. The project was over in July 2006. Note that thermo-mechanics of bridge piles combined with an *ad hoc* estimation of thermal gradients becomes of interest to practicing engineers. Thus, I4S's approach should suit advanced professional practice. Finite element analysis is also used to predict stresses and displacements of large bridges in Hong-Kong bay .

Temperature rejection is the primary focus and obstacle for SHM projects I4S participates in civil engineering, like SIMS project in Canada, ISMS in Danemark or SIPRIS in France.

A recent collaboration between Inria and IFSTTAR has demonstrated the efficiency of refractometry-based methods for health monitoring of some civil engineering structures, notably external post-tensioned cables. Based on a mathematical model of electromagnetic propagation in mechanical structures, the measurement of reflected and transmitted electromagnetic waves by the monitored structures allows to detect structural failures. The interaction of such methods with those based on mechanical and thermal measurements will reinforce the multidisciplinary approach developed in our team.

2.1.2.3. Models for monitoring under environmental changes - scientific background

We will be interested in studying linear stochastic systems, more precisely, assume at hand a sequence of observations Y_n measured during time,

$$\left\{ \begin{array}{rcl} X_{n+1} & = & AX_n + V_n \\ Y_n & = & HX_n \end{array} \right. \tag{1}$$

where V_n is a zero mean process, A is the transition matrix of the system, H is the observation matrix between state and observation, and X_n the process describing the monitored system. X_n can be related to a physical process (for example, for a mechanical structure, the collection of displacements and velocities at different points). Different problems arise

1/ identify and characterize the structure of interest. It may be possible by matching a parametric model to the observed time series Y_n in order to minimize some given criterion, whose minimum will be the best approximation describing the system,

2/ decide if the measured data describe a system in a so called "reference" state (the term "reference" is used in the context of fault detection, where the reference is considered to be safe) and monitor its deviations with respect of its nominal reference state.

Both problems should be addressed differently if

1/ we consider that the allocated time to measurement is large enough, resulting in a sequence Y_n whose size tends to infinity, a requirement for obtaining statistical convergence results. It corresponds to the identification and monitoring of a dynamical system with slow variations. For example, this description is well suited to the long-term monitoring of civil structures, where records can be measured during relatively (to sampling rate) large periods of time (typically many minutes or hours).

2/ we are interested in systems, whose dynamic is fast with respect to the sampling rate, most often asking for reaction in terms of seconds. It is, for example, the case for mission critical applications such as in-flight control or real-time security and safety assessment. Both aeronautics and transport or utilities infrastructures are concerned. In this case, fast algorithms with sample-by-sample reaction are necessary.

The monitoring of mechanical structures can not be addressed without taking into account the close environment of the considered system and their interactions. Typically, monitored structures of interest do not reside in laboratory but are considered in operational conditions, undergoing temperature, wind and humidity variations, as well as traffic, wind, water flows and other natural or man-made loads. Those variations do imply a variation of the eigenproperties of the monitored structure, variations to be separated from the damage/instability induced variations.

For example, in civil engineering, an essential problem for in operation health monitoring of civil structures is the variation of the environment itself. Unlike laboratory experiments, civil structure modal properties change during time as temperature and humidity vary. Traffic and comparable transient events also influence the structures. Thus, structural modal properties are modified by slow low variations, as well as fast transient non stationarities. From a damage detection point of view, the former has to be detected, whereas the latter has to be neglected and not perturb the detection. Of course, from a structural health monitoring point of view the knowledge of the true load is in itself of paramount importance.

In this context, the considered perturbations will be of two kinds, either

1/ the influence of the temperature on civil structures, such as bridges or wind energy converters : as we will notice, those induced variations can be modeled by a additive component on the system stiffness matrix depending on the current temperature, as

$$K = K_{struct} + K_T \ .$$

We will then have to monitor the variations in K_{struct} independently of the variations in K_T, based on some measurements generated from a system, whose stiffness matrix is K.

2/ the influence of the aeroelastic forces on aeronautical structures such as aircrafts or rockets and on flexible civil structures such as long-span bridges : we will see as well that this influence implies a modification of the usual mechanical equation (2) as

$$M\ddot{Z} + C\dot{Z} + KZ = V \tag{2}$$

where (M, C, K) are the mass, damping and stiffness matrices of the system and Z the associated vector of displacements measured on the monitored structure. In a first approximation, those quantities are related by (2). Assuming U is the velocity of the system, adding U dependent aeroelasticity terms, as in (3), introduces a coupling between U and (M, C, K).

$$M\ddot{Z} + C\dot{Z} + KZ = U^2 DZ + UE\dot{Z} + V \tag{3}$$

Most of the research at Inria for a decade has been devoted to the study of subspace methods and how they handle the problems described above.

Model (2) is characterized by the following property (we formulate it for the single sensor case, to simplify notations): Let $y_{-N} \cdots y_{+N}$ be the data set, where N is large, and let M, P sufficiently smaller than N for the following objects to make sense: 1/ define the row vectors $Y_k = (y_k \cdots y_{k-M}), |k| \leq P$; 2/ stack the Y_k on top of each other for $k = 0, 1, \cdots, P$ to get the data matrix $\mathcal{Y}_+$ and stack the column vectors Y_k^T for $k = 0, -1, \cdots, -P$ to get the data matrix $\mathcal{Y}_-$; 3/ the product $\mathcal{H} = \mathcal{Y}_+ \mathcal{Y}_-$ is a Hankel matrix. Then, matrix $\mathcal{H}$ on the one hand, and the observability matrix $\mathcal{O}(H, F)$ of system (2) on the other hand, possess almost identical left kernel spaces, asymptotically for M, N large. This property is the basis of subspace identification methods. Extracting $\mathcal{O}(H, F)$ using some Singular Value Decomposition from $\mathcal{H}$ then (H, F) from $\mathcal{O}(H, F)$ using a Least Square approach has been the foundation of the academic work on subspace methods for many years. The team focused on the numerical efficiency and consistency of those methods and their applicability on solving the problems above.

There are numerous ways to implement those methods. This approach has seen a wide acceptance in the industry and benefits from a large background in the automatic control literature. Up to now, there was a discrepancy between the a prior efficiency of the method and some not so efficient implementations of this algorithm. In practice, for the last ten years, stabilization diagrams have been used to handle the instability and the weakness with respect to noise, as well as the poor capability of those methods to determine model orders from data. Those methods implied some engineering expertise and heavy post processing to discriminate between models and noise. This complexity has led the mechanical community to adopt preferably frequency domain methods such as Polyreference LSCF. Our focus has been on improving the numerical stability of the subspace algorithms by studying how to compute the least square solution step in this algorithm. This yields to a very efficient noise free algorithm, which has provided a renewed acceptance in the mechanical engineering community for the subspace algorithms. Now we focus on improving speed and robustness of those algorithms.

Subspace methods can also be used to test whether a given data set conforms a model: just check whether this property holds, for a given pair {data, model}. Since equality holds only asymptotically, equality must be tested against some threshold ε; tuning ε relies on so-called *asymptotic local* approach for testing between close hypotheses on long data sets — this method was introduced by Le Cam in the 70s. By using the Jacobian between pair (H, F) and the modes and mode shapes, or the Finite Element Model parameters, one can localize and assess the damage.

In oder to discriminate between damage and temperature variations, we need to monitor the variations in K_{struct} while keeping blind to the variations in K_T in statistical terms, we must detect and diagnose changes in K_{struct} while rejecting nuisance parameter K_T. Several techniques were explored in the thesis of Houssein Nasser, from purely empirical approaches to (physical) model based approaches. Empirical approaches do work, but model based approaches are the most promising and a focus of our future researches. This approach requires a physical model of how temperature affects stiffness in various materials. This is why a large part of our future research is devoted to the modeling of such environmental effect.

This approach has been used also for flutter monitoring in the thesis of Rafik Zouari for handling the aeroelastic effect.

2.1.3. PEGASE platform development

We have developed a generic wireless platform that can be considered as the a result of redundant needs in wireless monitoring especially applied to civil engineering monitoring applications. This platform includes software and hardware bricks and aims at being generic by its native implementation of sober components, the worldwide TCP/IP protocol (802.11g), a signal processor, a small GPS receiver, and a micro embedded operating system (μClinux).

Since 2009, this platform -named PEGASE - is subject of an industrial transfer that has generated some tens of individual sales. A set of pluggable boards (that integrate the application specific sensing operation) offers a ready-to-use panel of wireless sensing solutions for developing specific applications as well as they can be seen as prototyping boards for further electronic developments.

As PEGASE platform reached a mature level of dissemination, IFSTTAR recent efforts are now leaded with the goal of improving its wireless capacities. Those works concern energy saving while keeping a high level of embedded processing, of sampling rate or time-synchronization.

As software layers are mainly written in standard C language under Linux OS, those pragmatic solutions could easily be re-used by even radically different systems. The focus will specifically be pointed on: an algorithm that allows PEGASE wireless boards to be synchronized up to some uS using a GPS technique while keeping the GPS receiver OFF most of the time; a description of how the use of an operating system such as μClinux allows a full and remotely update of wireless sensors; the hardware and software strategies that have been developed to make PEGASE fully autonomous using solar cells.

The main characteristics of PEGASE feature are the following:

- Use of TCP/IP/WiFi as the wireless protocol: reliable, low-cost, scalable (IP is the worldwide protocol). Turned OFF when PEGASE doesn't communicate.
- Use of the Analog Device low-power Blackfin BF537 as core processor (Digital Signal Processor): 16 bits processor able of complex operations.
- Implementation of a small and low-power GPS receiver to ensure localization and, first of all, absolute time synchronization up to few μ ms GMT.

- μClinux as the embedded operating system: allows high level of abstraction while PEGASE algorithms are then programmed using standard ANSI C language.

Since its first version on January 2008, PEGASE has been used in various configurations where its properties fitted specific needs. Since a third-party partner (A3IP company) has been licensed by IFSTTAR, PEGASE has been sold in hundreds of specimens and implemented in various configurations. This dissemination proved the capacity of wireless systems to really answer a large spectrum of applications. Developments in progress have the goal to increase this panoply. Even if μClinux and WiFi integration could be considered as *heavy*, the result is a great ability for developers or customers to achieve their own applications. The genericity of C language and the worldwide IP protocol make them ubiquitous. A quite expert job has been leaded to develop specific embedded drivers under μClinux OS in order to get specific behaviors for time synchronization, quartz drift auto-training and correction. This specific and dynamic correction takes temperature effects into account and the result is an absolute time synchronisation better that 4 μS. Even if technologies evolve (components, processor, batteries...), generic principle could be extracted independently from technological choices. Those main principles are: daughter/mother boards, Linux integration, a ready to use c-object library, a boost circuit linked to a MPPT algorithm, GPS synchronization and quartz correction. Most of the improvements can be reused and applied to other wireless platforms even using drastically different electronic implementations.

PEGASE platform has the goal to represent an adapted tool to help companies and laboratories in their instrumentation needs in Civil Engineering applications, Structural Health Monitoring in general and for Non Destructive Techniques tools design. Initial version of PEGASE has been sold in hundreds of samples in France or Europe to small or significant companies such as Vinci, Eurovia, SNCF, Cofiroute...

3. Research Program

3.1. Vibration analysis

In this section, the main features for the key monitoring issues, namely identification, detection, and diagnostics, are provided, and a particular instantiation relevant for vibration monitoring is described.

It should be stressed that the foundations for identification, detection, and diagnostics, are fairly general, if not generic. Handling high order linear dynamical systems, in connection with finite elements models, which call for using subspace-based methods, is specific to vibration-based SHM. Actually, one particular feature of model-based sensor information data processing as exercised in I4S, is the combined use of black-box or semi-physical models together with physical ones. Black-box and semi-physical models are, for example, eigenstructure parameterizations of linear MIMO systems, of interest for modal analysis and vibration-based SHM. Such models are intended to be identifiable. However, due to the large model orders that need to be considered, the issue of model order selection is really a challenge. Traditional advanced techniques from statistics such as the various forms of Akaike criteria (AIC, BIC, MDL, ...) do not work at all. This gives rise to new research activities specific to handling high order models.

Our approach to monitoring assumes that a model of the monitored system is available. This is a reasonable assumption, especially within the SHM areas. The main feature of our monitoring method is its intrinsic ability to the early warning of small deviations of a system with respect to a reference (safe) behavior under usual operating conditions, namely without any artificial excitation or other external action. Such a normal behavior is summarized in a reference parameter vector θ_0, for example a collection of modes and mode-shapes.

3.1.1. Identification

The behavior of the monitored continuous system is assumed to be described by a parametric model $\{\mathbf{P}_\theta\, , \, \theta \in \Theta\}$, where the distribution of the observations $(Z_0, ..., Z_N)$ is characterized by the parameter vector $\theta \in \Theta$.

For reasons closely related to the vibrations monitoring applications, we have been investigating subspace-based methods, for both the identification and the monitoring of the eigenstructure (λ, ϕ_λ) of the state transition matrix F of a linear dynamical state-space system :

$$\begin{cases} X_{k+1} &= F\ X_k + V_{k+1} \\ Y_k &= H\ X_k \end{cases}, \tag{4}$$

namely the $(\lambda, \varphi_\lambda)$ defined by :

$$\det\ (F - \lambda\ I) = 0, \quad (F - \lambda\ I)\ \phi_\lambda = 0, \quad \varphi_\lambda \triangleq H\ \phi_\lambda \tag{5}$$

The (canonical) parameter vector in that case is :

$$\theta \triangleq \begin{pmatrix} \Lambda \\ \text{vec}\Phi \end{pmatrix} \tag{6}$$

where Λ is the vector whose elements are the eigenvalues λ, Φ is the matrix whose columns are the φ_λ's, and vec is the column stacking operator.

Subspace-based methods is the generic name for linear systems identification algorithms based on either time domain measurements or output covariance matrices, in which different subspaces of Gaussian random vectors play a key role [53].

Let $R_i \triangleq \mathbf{E}\left(Y_k\ Y_{k-i}^T\right)$ and:

$$\mathcal{H}_{p+1,q} \triangleq \begin{pmatrix} R_0 & R_1 & \vdots & R_{q-1} \\ R_1 & R_2 & \vdots & R_q \\ \vdots & \vdots & \vdots & \vdots \\ R_p & R_{p+1} & \vdots & R_{p+q-1} \end{pmatrix} \triangleq \text{Hank}\,(R_i) \tag{7}$$

be the output covariance and Hankel matrices, respectively; and: $G \triangleq \mathbf{E}\left(X_k Y_k^T\right)$. Direct computations of the R_i's from the equations (4) lead to the well known key factorizations :

$$\begin{aligned} R_i &= HF^iG \\ \mathcal{H}_{p+1,q} &= \mathcal{O}_{p+1}(H,F)\ \mathcal{C}_q(F,G) \end{aligned} \tag{8}$$

where:

$$\mathcal{O}_{p+1}(H,F) \triangleq \begin{pmatrix} H \\ HF \\ \vdots \\ HF^p \end{pmatrix} \quad \text{and} \quad \mathcal{C}_q(F,G) \triangleq (G\ FG\ \cdots\ F^{q-1}G) \tag{9}$$

are the observability and controllability matrices, respectively. The observation matrix H is then found in the first block-row of the observability matrix $\mathcal{O}$. The state-transition matrix F is obtained from the shift invariance property of $\mathcal{O}$. The eigenstructure (λ, ϕ_λ) then results from (5).

Since the actual model order is generally not known, this procedure is run with increasing model orders.

3.1.2. Detection

Our approach to on-board detection is based on the so-called asymptotic statistical local approach. It is worth noticing that these investigations of ours have been initially motivated by a vibration monitoring application example. It should also be stressed that, as opposite to many monitoring approaches, our method does not require repeated identification for each newly collected data sample.

For achieving the early detection of small deviations with respect to the normal behavior, our approach generates, on the basis of the reference parameter vector θ_0 and a new data record, indicators which automatically perform :

- The early detection of a slight mismatch between the model and the data;
- A preliminary diagnostics and localization of the deviation(s);
- The tradeoff between the magnitude of the detected changes and the uncertainty resulting from the estimation error in the reference model and the measurement noise level.

These indicators are computationally cheap, and thus can be embedded. This is of particular interest in some applications, such as flutter monitoring.

Choosing the eigenvectors of matrix F as a basis for the state space of model (4) yields the following representation of the observability matrix:

$$\mathcal{O}_{p+1}(\theta) = \begin{pmatrix} \Phi \\ \Phi\Delta \\ \vdots \\ \Phi\Delta^p \end{pmatrix} \tag{10}$$

where $\Delta \triangleq \mathrm{diag}(\Lambda)$, and Λ and Φ are as in (6). Whether a nominal parameter θ_0 fits a given output covariance sequence $(R_j)_j$ is characterized by:

$$\mathcal{O}_{p+1}(\theta_0) \text{ and } \mathcal{H}_{p+1,q} \text{ have the same left kernel space.} \tag{11}$$

This property can be checked as follows. From the nominal θ_0, compute $\mathcal{O}_{p+1}(\theta_0)$ using (10), and perform e.g. a singular value decomposition (SVD) of $\mathcal{O}_{p+1}(\theta_0)$ for extracting a matrix U such that:

$$U^T\, U = I_s \text{ and } U^T\, \mathcal{O}_{p+1}(\theta_0) = 0 \tag{12}$$

Matrix U is not unique (two such matrices relate through a post-multiplication with an orthonormal matrix), but can be regarded as a function of θ_0. Then the characterization writes:

$$U(\theta_0)^T\, \mathcal{H}_{p+1,q} = 0 \tag{13}$$

3.1.2.1. Residual associated with subspace identification.

Assume now that *a reference* θ_0 *and a new sample* $Y_1, \cdots, Y_N$ *are available.* For checking whether the data agree with θ_0, the idea is to compute the empirical Hankel matrix $\widehat{\mathcal{H}}_{p+1,q}$:

$$\widehat{\mathcal{H}}_{p+1,q} \triangleq \mathrm{Hank}\left(\widehat{R}_i\right), \quad \widehat{R}_i \triangleq 1/(N-i) \sum_{k=i+1}^{N} Y_k\, Y_{k-i}^T \tag{14}$$

and to define the residual vector:

$$\zeta_N(\theta_0) \triangleq \sqrt{N}\ \mathrm{vec}\left(U(\theta_0)^T\ \widehat{\mathcal{H}}_{p+1,q}\right) \tag{15}$$

Let θ be the actual parameter value for the system which generated the new data sample, and $\mathbf{E}_\theta$ be the expectation when the actual system parameter is θ. From (13), we know that $\zeta_N(\theta_0)$ has zero mean when no change occurs in θ, and nonzero mean if a change occurs. Thus $\zeta_N(\theta_0)$ plays the role of a residual.

As in most fault detection approaches, the key issue is to design a *residual*, which is ideally close to zero under normal operation, and has low sensitivity to noises and other nuisance perturbations, but high sensitivity to small deviations, before they develop into events to be avoided (damages, faults, ...). The originality of our approach is to :

- *Design* the residual basically as a *parameter estimating function*,
- *Evaluate* the residual thanks to a kind of central limit theorem, stating that the residual is asymptotically Gaussian and reflects the presence of a deviation in the parameter vector through a change in its own mean vector, which switches from zero in the reference situation to a non-zero value.

The central limit theorem shows [47] that the residual is asymptotically Gaussian :

$$\zeta_N \xrightarrow[N\to\infty]{} \left\{ \begin{array}{ll} \mathcal{N}(0,\Sigma) & \text{under } \mathbf{P}_{\theta_0}\ , \\ \\ \mathcal{N}(\mathcal{J}\,\eta,\Sigma) & \text{under } \mathbf{P}_{\theta_0+\eta/\sqrt{N}}\ , \end{array} \right. \tag{16}$$

where the asymptotic covariance matrix Σ can be estimated, and manifests the deviation in the parameter vector by a change in its own mean value. Then, deciding between $\eta = 0$ and $\eta \neq 0$ amounts to compute the following χ^2-test, provided that $\mathcal{J}$ is full rank and Σ is invertible :

$$\chi^2 = \overline{\zeta}^{\,T}\, \mathbf{F}^{-1}\, \overline{\zeta} \gtrless \lambda\ . \tag{17}$$

where

$$\overline{\zeta} \triangleq \mathcal{J}^T\, \Sigma^{-1}\, \zeta_N \quad \text{and} \quad \mathbf{F} \triangleq \mathcal{J}^T\, \Sigma^{-1}\, \mathcal{J} \tag{18}$$

3.1.3. Diagnostics

A further monitoring step, often called *fault isolation*, consists in determining which (subsets of) components of the parameter vector θ have been affected by the change. Solutions for that are now described. How this relates to diagnostics is addressed afterwards.

The question: *which (subsets of) components of θ have changed ?*, can be addressed using either nuisance parameters elimination methods or a multiple hypotheses testing approach [46].

In most SHM applications, a complex physical system, characterized by a generally non identifiable parameter vector Φ has to be monitored using a simple (black-box) model characterized by an identifiable parameter vector θ. A typical example is the vibration monitoring problem for which complex finite elements models are often available but not identifiable, whereas the small number of existing sensors calls for identifying only simplified input-output (black-box) representations. In such a situation, two different diagnosis problems may arise, namely diagnosis in terms of the black-box parameter θ and diagnosis in terms of the parameter vector Φ of the underlying physical model.

The isolation methods sketched above are possible solutions to the former. Our approach to the latter diagnosis problem is basically a detection approach again, and not a (generally ill-posed) inverse problem estimation approach.

The basic idea is to note that the physical sensitivity matrix writes $\mathcal{J}\,\mathcal{J}_{\Phi\theta}$, where $\mathcal{J}_{\Phi\theta}$ is the Jacobian matrix at Φ_0 of the application $\Phi \mapsto \theta(\Phi)$, and to use the sensitivity test for the components of the parameter vector Φ. Typically this results in the following type of directional test :

$$\chi^2_\Phi = \zeta^T\,\Sigma^{-1}\,\mathcal{J}\,\mathcal{J}_{\Phi\theta}\,(\mathcal{J}^T_{\Phi\theta}\,\mathcal{J}^T\,\Sigma^{-1}\,\mathcal{J}\,\mathcal{J}_{\Phi\theta})^{-1}\,\mathcal{J}^T_{\Phi\theta}\,\mathcal{J}^T\,\Sigma^{-1}\,\zeta \gtrless \lambda\ . \tag{19}$$

It should be clear that the selection of a particular parameterization Φ for the physical model may have a non negligible influence on such type of tests, according to the numerical conditioning of the Jacobian matrices $\mathcal{J}_{\Phi\theta}$.

3.2. Thermal methods

3.2.1. Infrared vision and measurement Method

This section introduce the infrared radiation and its link with the temperature, in the next part different measurement methods based on that principle are presented.

3.2.1.1. Infrared radiation

Infrared is an electromagnetic radiation having a wavelength between $0.7\ \mu m$ and $1\ mm$, this range begin early after the visible spectrum and it ends on the microwaves domain, see Figure 1.

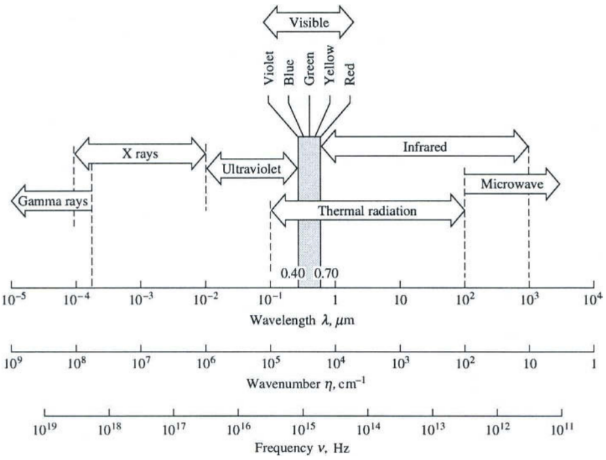

Figure 1. Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

For scientific purpose infrared can be divided in three ranges of wavelength in which the application varies, see Table 1.

Table 1. Wavelength bands in the infrared according to ISO 20473:2007

Band name	**wavelength**	**Uses $\setminus$ definition**
Near infrared (PIR, IR-A, NIR)	$0.7 - 3\mu$m	Reflected solar heat flux
Mid infrared (MIR, IR-B)	$3 - 50\mu$m	Thermal infrared
Far infrared (LIR, IR-C, FIR)	$50 - 1000\mu$m	Astronomy

Our work is concentrated in the mid infrared spectral band. Keep in mind that Table 1 represents the ISO 20473 division scheme, in the literature boundaries between bands can move slightly.
The Plank's law, proposed by Max Planck en 1901, allow to compute the black body emission spectrum for various temperatures (and only temperatures), see Figure 2 left. The black body is a theoretical construction, it represents perfect energy transmitter at a given temperature, cf Equation (20).

$$M^{o}_{\lambda,T} = \frac{C_1 \lambda^{-5}}{\exp^{\frac{C_2}{\lambda T}} - 1} \tag{20}$$

With λ the wavelength in m and T as the temperature in Kelvin. The C_1 an C_2 constant, respectively in kg.m^4.s^{-3} and m.K are defined as follow:

$$\begin{aligned} C_1 &= 2hc^2\pi \\ C_2 &= h\frac{c}{k} \end{aligned} \tag{21}$$

with

- c The electromagnetic wave speed (in vacuum c is the light speed in m.s^{-1}).
- $k = 1.381e^{-23}$ J.K^{-1} The Boltzmann (Entropy definition from Ludwig Boltzmann 1873). It can be seen as a proportionality factor between the temperature and the energy of a system.
- $h \approx 6,62606957e^{-34}$ J.s The Plank constant. It's the link between the photons energy and their frequency.

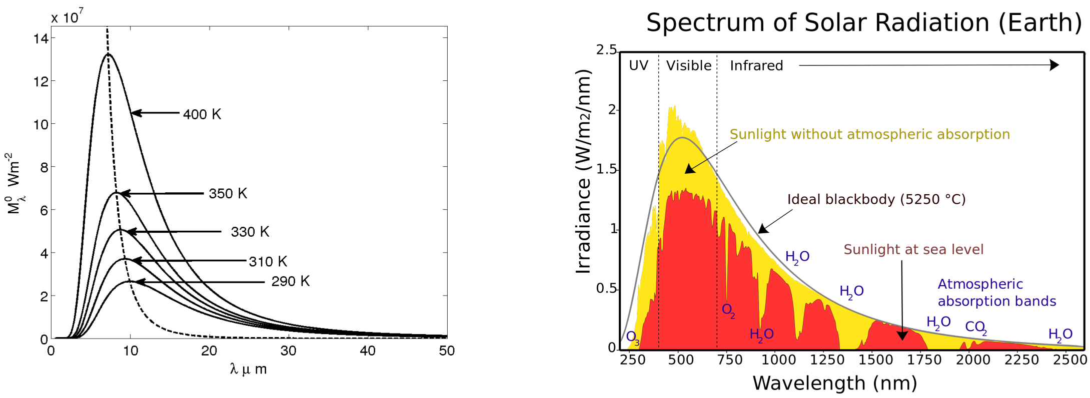

Figure 2. Left: Plank's law at various temperatures - Right: Energy spectrum of the atmosphere

By generalizing the Plank's law with the Stefan Boltzmann law (proposed first in 1879 and then in 1884 by Joseph Stefan and Ludwig Boltzmann) it's possible to address mathematically the energy spectrum of real body at each wavelength dependent of the temperature, the optical condition and the real body properties, which is the base of the infrared thermography, cf Equation (22).

$$\begin{aligned} \varphi_\lambda &= \underbrace{\sigma_s T_o^4}_{\text{Balck body emission}} - \overbrace{\left[\underbrace{\epsilon_\lambda \sigma_s T^4}_{\text{Real body emission}} - \underbrace{(1-\epsilon_\lambda)\,\sigma_s T_o^4}_{\text{reflexion}} \right]}^{\text{Real body radiosity}} \\ \varphi_\lambda &= \epsilon_\lambda \sigma_s \left(T_o^4 - T^4\right) \end{aligned} \tag{22}$$

where

- $\sigma_s = 5,67.10^{-8}$ W.m^{-2}.K^{-4} The Stephan constant
- ϵ_λ The emissivity ratio of the real body at a given wavelength (For the black body $\epsilon \forall \lambda = 1$)
- φ_λ The energy flux in Wm^{-2} at a given wavelength

For example, Figure 2 right presents the energy spectrum of the atmosphere at various levels, it can be seen that the various properties of the atmosphere affect the spectrum at various wavelengths. Other important point is that the infrared solar heat flux can be approximated by a black body at 5523,15 K.
The above demonstrations are here to illustrate how energy and temperature can be linked, this can only be used as an general purpose introduction for the next sections.

3.2.1.2. Infrared Thermography

The infrared thermography is a way to measure the thermal radiation emitted or reflected by a medium. With that information about the electromagnetic flux it's possible to compute the surface temperature of the body, see section 3.2.1.1. Various types of detector can assure the measure of the electromagnetic radiation. Table 2 illustrates for various spectral bands in infrared some of the detectors which can be used to measure the thermal radiation.

Table 2. Infrared sensors

Bands	**Wavelength**	**Detectors**
Near Infrared	$0.7 - 1\mu m$	End of the human eye response, Aluminium gallium arsenide detectors (InGaAs)
Short Wave Infrared - SWIR\Band I	$1 - 3\mu m$	Germanium detector ans InGaAs
Mid Wave Infrared - MWIR\Band II	$3 - 5\mu m$	Mercury cadmium telluride detectors (HgCdTe), Lead selenide (PbSe) and InSb
Long wave Infrared - LWIR\Band III	$7 - 14\mu m$	Microbolometers (VOx) and HgCdTe
Very long wave infrared	$12 - 30\mu m$	silicon detectors

Those different detectors can take various forms and/or manufacturing process. For our research purpose we use uncooled infrared camera using a matrix of microbolometers detectors. A microbolometer, as a lot of transducers, converts a radiation in electric current used to represent the physical quantity (here the heat flux). Figure 3 shows an example of FLIR AX5 low cost mini infrared camera that we use for long term SHM purpose, and also a schematic representation of the measurement principle.
This field of activity includes the use and the improvement of vision system, like in [6].

3.2.2. Heat transfer theory

Once the acquisition process is done, it's useful to model the heat conduction inside the cartesian domain Ω. Note that in opaque solid medium the heat conduction is the only mode of heat transfer. Proposed by Jean Baptiste Biot in 1804 and experimentally demonstrated by Joseph Fourier in 1821, the Fourier Law describes the heat flux inside a solid, cf Equation (23).

$$\varphi = k \nabla T \quad X \in \Omega \tag{23}$$

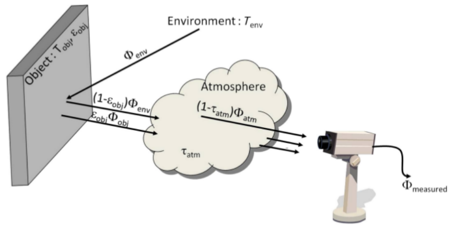

Figure 3. Left: AX5 low cost camera - Right: Example of measurement process [6]

Where k is the thermal conductivity in W.m^{-1}.K ^{o}, ∇ is the gradient operator and φ is the heat flux density in Wm^{-2}. This law illustrates the first principle of thermodynamic (law of conservation of energy) and implies the second principle (irreversibility of the phenomenon), from this law it can be seen that the heat flux always goes from hot area to cold area.
An energy balance with respect to the first principle drives to the expression of the heat conduction in all point of the domain Ω, cf Equation (24). This equation has been proposed by Joseph Fourier in 1811.

$$\rho C \frac{\partial T(X,t)}{\partial t} = \nabla \cdot (k \nabla T) + P \quad X \in \Omega \tag{24}$$

With $\nabla.()$ the divergence operator, C the specific heat capacity in J.kg^{-1}.^{o}K^{-1}, ρ the volumetric mass density in kg. m^{-3}, X the space variable $X = \{x, y, z\}$ and P a possible internal heat production in W.m^{-3}.
To solve the system (24), it's necessary to express the boundaries conditions of the system. With the developments presented in section 3.2.1.1 and the Fourier's law it's possible, for example, to express the thermal radiation and the convection phenomenon which can occur at $\partial\Omega$ the system boundaries, cf Equation (25).

$$\varphi = k \nabla T \cdot n = \underbrace{h \left(T_{fluid} - T_{Boundarie}\right)}_{\text{Convection}} + \underbrace{\epsilon \sigma_s \left(T^4_{environement} - T^4_{Boundary}\right)}_{\text{Radiation}} + \varphi_0 \quad X \in \partial\Omega \tag{25}$$

Equation (25) is the so called Robin condition on the boundary $\partial\Omega$, where n is the normal, h the convective heat transfer coefficient in W.m^{-2}.K^{-1} and φ_0 an external energy contribution W.m^{-2}, in cases where the external energy contribution is artificial and controlled we call it active thermography (spotlight etc...) in the contrary it's called passive thermography (direct solar heat flux).
The systems presented in the different sections above (3.2.1 to 3.2.2) are useful to build physical models in order to represents the measured quantity. To estimate key parameters, as the conductivity, one way to do is the model inversion, the next section will introduce that principle.

3.2.3. Inverse model for parameters estimation

Lets take any model A which can for example represent the conductive heat transfer in a medium, the model is solved for a parameter vector P and it results another vector b, cf Equation (26). For example if A represents the heat transfer, b can be the temperature evolution.

$$AP = b \tag{26}$$

With A a matrix of size $n \times m$, P a vector of size m and b of size n, preferentially $n >> P$. This model is called direct model, the inverse model consist to find a vector P which satisfy the results b of the direct model. For that we need to inverse the matrix A, cf Equation (27).

$$P = A^{-1}b \tag{27}$$

Here we want find the solution AP which is closest to the acquired measures M, Equation (28).

$$AP \approx \mathcal{M} \tag{28}$$

To do that it's important to respect the well posed condition established by Jacques Hadamard in 1902

- A solution exists.
- The solution is unique.
- The solution's behavior changes continuously with the initial conditions.

Unfortunately those condition are rarely respected in our field of study. That's why we dont solve directly the system (28) but we minimise the quadratic coast function (29) which represents the Legendre-Gauss least square algorithm for linear problems.

$$min_P \left(\|AP - \mathcal{M}\|^2 \right) = min_P \left(\mathcal{F} \right) \tag{29}$$

Where $\mathcal{F}$ can be a product of matrix.

$$\mathcal{F} = [AP - \mathcal{M}]^T [AP - \mathcal{M}] \tag{30}$$

In some case the problem is still ill-posed and need to be regularized for example using the Tikhonov regularization. An elegant way to minimize the cost function $\mathcal{F}$ is compute the gradient, Equation (31) and find where it's equal to zero..

$$\nabla\mathcal{F}(P) = 2 \left[-\frac{\partial AP^T}{\partial P} \right] [AP - \mathcal{M}] = 2J(P)^T [AP - \mathcal{M}] \tag{31}$$

Where J is the sensitivity matrix of the model A to its parameter vector P.
Until now the inverse method proposed is valid only when the model A is linearly dependent of its parameter P, for the heat equation it's the case when you want to estimate the external heat flux, φ_0 in equation 25. For all the other parameters, like the conductivity k the model is non-linearly dependant of its parameter P. For such case the use of iterative algorithm is needed, for example the Levenberg-Marquardt algorithm, cf Equation (32).

$$P^{k+1} = P^k + \left[\left(J^k\right)^T J^k + \mu^k \Omega^k \right]^{-1} \left(J^k\right)^T \left[\mathcal{M} - A(P^k) \right] \tag{32}$$

Equation (32) is solved iteratively at each loop k. Some of our results with such linear or non linear method can be seen in [7] or [2], more specifically [1] is a custom implementation of the Levenberg-Marquardt algorithm based on the adjoin method (developed by Jacques Louis Lions in 1968) coupled to the conjugate gradient algorithm to estimate wide properties field in a medium.

3.3. Reflectometry-based methods for electrical engineering and for civil engineering

The fast development of electronic devices in modern engineering systems involves more and more connections through cables, and consequently, with an increasing number connexion failures. Wires and connectors are subject to aging and degradation, sometimes under severe environmental conditions. In many applications, the reliability of electrical connexions is related to the quality of production or service, whereas in critical applications reliability becomes also a safety issue. It is thus important to design smart diagnosis systems able to detect connection defects in real time. This fact has motivated research projects on methods for fault diagnosis in this field. Some of these projects are based on techniques of reflectometry, which consist in injecting waves into a cable or a network and in analyzing the reflections, as in the example of cable hard fault diagnosis illustrated in Figure 4. Depending on the injected waveforms and on the methods of analysis, various techniques of reflectometry are available. They all have the common advantage of being non destructive.

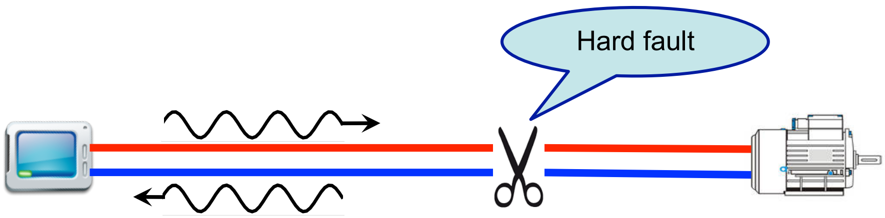

Figure 4. Reflectometry applied to cable hard fault diagnosis.

At Inria the research activities on reflectometry started within the SISYPHE EPI several years ago and now continue in the I4S EPI. Our most notable contribution in this area is a method based on the *inverse scattering* theory for the computation of *distributed characteristic impedance* along a cable from reflectometry measurements [14], [11], [52]. It provides an efficient solution for the diagnosis of *soft* faults in electrical cables, like in the example illustrated in Figure 5. While most reflectometry methods for fault diagnosis are based on the detection and location of impedance discontinuity, our method yielding the spatial profile of the characteristic impedance is particularly suitable for the diagnosis of soft faults *with no or weak impedance discontinuities*.

Fault diagnosis for wired networks have also been studied in Inria [54], [50]. The main results concern, on the one hand, simple star-shaped networks from measurements made at a single node, on the other hand, complex networks of arbitrary topological structure with complete node observations.

Though initially our studies on reflectometry were aiming at applications in electrical engineering, through our collaboration with IFSTTAR, we are also investigating applications in the field of civil engineering, by using electrical cables as sensors for monitoring changes in mechanical structures.

What follows is about some basic elements on mathematical equations of electric cables and networks, the main approach we follow in our study, and our future research directions.

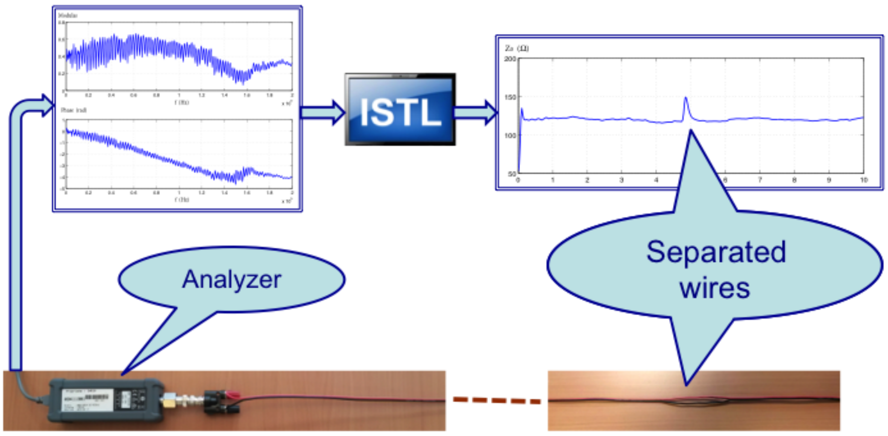

Figure 5. Inverse scattering software (ISTL) for cable soft fault diagnosis.

3.3.1. Mathematical model of electric cables and networks

A cable excited by a signal generator can be characterized by the telegrapher's equations [51]

$$\begin{aligned} \frac{\partial}{\partial z}V(t,z) + L(z)\frac{\partial}{\partial t}I(t,z) + R(z)I(t,z) = 0 \\ \frac{\partial}{\partial z}I(t,z) + C(z)\frac{\partial}{\partial t}V(t,z) + G(z)V(t,z) = 0 \end{aligned} \tag{33}$$

where t represents the time, z is the longitudinal coordinate along the cable, $V(t,z)$ and $I(t,z)$ are respectively the voltage and the current in the cable at the time instant t and at the position z, $R(z)$, $L(z)$, $C(z)$ and $G(z)$ denote respectively the series resistance, the inductance, the capacitance and the shunt conductance per unit length of the cable at the position z. The left end of the cable (corresponding to $z = a$) is connected to a voltage source $V_s(t)$ with internal impedance R_s. The quantities $V_s(t)$, R_s, $V(t,a)$ and $I(t,a)$ are related by

$$V(t,a) = V_s(t) - R_sI(t,a). \tag{34}$$

At the right end of the cable (corresponding to $z = b$), the cable is connected to a load of impedance R_L, such that

$$V(t,b) \quad = R_LI(t,b). \tag{35}$$

One way for deriving the above model is to spatially discretize the cable and to characterize each small segment with 4 basic lumped parameter elements, as illustrated in Figure 6 for the j-th segment: a resistance ΔR_j, an inductance ΔL_j, a capacitance ΔC_j and a conductance ΔG_j. The entire circuit is described by a system of ordinary differential equations. When the spatial discretization step size tends to zero, the limiting model leads to the telegrapher's equations (33).

A wired network is a set of cables connected at some nodes, where loads and sources can also be connected. Within each cable the current and voltage satisfy the telegrapher's equations (33), whereas at each node the current and voltage satisfy the Kirchhoff's laws, unless in case of connector failures. .

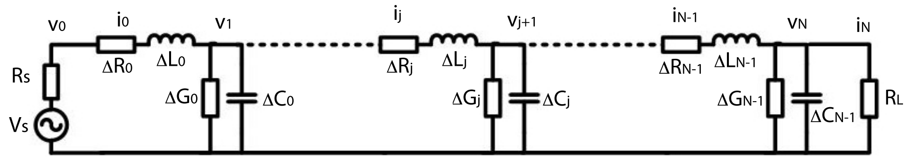

Figure 6. Spatially discretized cable model.

3.3.2. The inverse scattering theory applied to cables

The inverse scattering transform was developed during the 1970s-1980s for the analysis of some nonlinear partial differential equations [49]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [48]. After having completed some theoretic results directly linked to practice [14], [52], we started to successfully apply the inverse scattering theory to cable soft fault diagnosis, in collaboration with GEEPS-SUPELEC [16].

To link electric cables to the inverse scattering theory, the telegrapher's equations (33) are transformed in a few steps to fit into a particular form studied in the inverse scattering theory. The Fourier transform is first applied to transform the time domain model (33) into the frequency domain, the spatial coordinate z is then replaced by the propagation time

$$x(z) = \int_0^z \sqrt{L(s)C(s)}ds$$

and the frequency domain variables $V(\omega, x), I(\omega, x)$ are replaced by the pair

$$\begin{aligned} \nu_1(\omega, x) &= \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega, x) - Z_0^{\frac{1}{2}}(x)I(\omega, x)\right] \\ \nu_2(\omega, x) &= \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega, x) + Z_0^{\frac{1}{2}}(x)I(\omega, x)\right] \end{aligned} \tag{36}$$

with

$$Z_0(x) = \sqrt{\frac{L(x)}{C(x)}}. \tag{37}$$

These transformations lead to the Zakharov-Shabat equations

$$\begin{aligned} \frac{d\nu_1(\omega, x)}{dx} + ik\nu_1(\omega, x) &= q^*(x)\nu_1(\omega, x) + q^+(x)\nu_2(\omega, x) \\ \frac{d\nu_2(\omega, x)}{dx} - ik\nu_2(\omega, x) &= q^-(x)\nu_1(\omega, x) - q^*(x)\nu_2(\omega, x) \end{aligned} \tag{38}$$

with

$$
\begin{aligned}
q^{\pm}(x) &= -\frac{1}{4}\frac{d}{dx}\left[ln\frac{L(x)}{C(x)}\right] \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right] \\
&= -\frac{1}{2Z_0(x)}\frac{d}{dx}Z_0(x) \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right] \\
q^{*}(x) &= \frac{1}{2}\left[\frac{R(x)}{L(x)} + \frac{G(x)}{C(x)}\right].
\end{aligned}
\tag{39}
$$

These equations have been well studied in the inverse scattering theory, for the purpose of determining partly the "potential functions" $q^{\pm}(x)$ and $q^{*}(x)$ from the scattering data matrix, which turns out to correspond to the data typically collected with reflectometry instruments. For instance, it is possible to compute the function $Z_0(x)$ defined in (37), often known as the characteristic impedance, from the reflection coefficient measured at one end of the cable. Such an example is illustrated in Figure 5. Any fault affecting the characteristic impedance, like in the example of Figure 5 caused by a slight geometric deformation, can thus be efficiently detected, located and characterized.

3.4. Research Program

The research will first focus on the extension and implementation of current techniques as developed in I4S and IFSTTAR. Before doing any temperature rejection on large scale structures as planned, we need to develop good and accurate models of thermal fields. We also need to develop robust and efficient versions of our algorithms, mainly the subspace algorithms before envisioning linking them with physical models. Briefly, we need to mature our statistical toolset as well as our physical modeling before mixing them together later on.

3.4.1. Vibration analysis and monitoring

3.4.1.1. Direct vibration modeling under temperature changes

This task builds upon what has been achieved in the CONSTRUCTIF project, where a simple formulation of the temperature effect has been exhibited, based on relatively simple assumptions. The next step is to generalize this modeling to a realistic large structure under complex thermal changes. Practically, temperature and resulting structural prestress and pre strains of thermal origin are not uniform and civil structures are complex. This leads to a fully 3D temperature field, not just a single value. Inertia effects also forbid a trivial prediction of the temperature based on current sensor outputs while ignoring past data. On the other side, the temperature is seen as a nuisance. That implies that any damage detection procedure has first to correct the temperature effect prior to any detection.

Modeling vibrations of structures under thermal prestress does and will play an important role in the static correction of kinematic measurements, in health monitoring methods based on vibration analysis as well as in durability and in the active or semi-active control of civil structures that by nature are operated under changing environmental conditions. As a matter of fact, using temperature and dynamic models the project aims at correcting the current vibration state from induced temperature effects, such that damage detection algorithms rely on a comparison of this thermally corrected current vibration state with a reference state computed or measured at a reference temperature. This approach is expected to cure damage detection algorithms from the environmental variations.

I4S will explore various ways of implementing this concept, notably within the FUI SIPRIS project.

3.4.1.2. Damage localization algorithms (in the case of localized damages such as cracks)

During the CONSTRUCTIF project, both feasibility and efficiency of some damage detection and localization algorithms were proved. Those methods are based on the tight coupling of statistical algorithms with finite element models. It has been shown that effective localization of some damaged elements was possible, and this was validated on a numerical simulated bridge deck model. Still, this approach has to be validated on real structures.

On the other side, new localization algorithms are currently investigated such as the one developed conjointly with University of Boston and tested within the framework of FP7 ISMS project. These algorithms will be implemented and tested on the PEGASE platform as well as all our toolset.

When possible, link with temperature rejection will be done along the lines of what has been achieved in the CONSTRUCTIF project.

3.4.1.3. Uncertainty quantification for system identification algorithms

Some emphasis will be put on expressing confidence intervals for system identification. It is a primary goal to take into account the uncertainty within the identification procedure, using either identification algorithms derivations or damage detection principles. Such algorithms are critical for both civil and aeronautical structures monitoring. It has been shown that confidence intervals for estimation parameters can theoretically be related to the damage detection techniques and should be computed as a function of the Fisher information matrix associated to the damage detection test. Based on those assumptions, it should be possible to obtain confidence intervals for a large class of estimates, from damping to finite elements models. Uncertainty considerations are also deeply investigated in collaboration with Dassault Aviation in Mellinger PhD thesis or with Northeastern University, Boston, within Gallegos PhD thesis.

3.4.2. Reflectometry-based methods for civil engineering structure health monitoring

The inverse scattering method we developed is efficient for the diagnosis of all soft faults affecting the characteristic impedance, the major parameter of a cable. In some particular applications, however, faults would rather affect the series resistance (ohmic loss) or shunt conductance (leakage loss) than the characteristic impedance. Currently, the algorithm we developed for the diagnosis of such losses lacks numerical stability. It is thus necessary to search for new solutions in order to cover most practical situations. It is also important to develop efficient solutions for long cables, up to a few kilometers.

For wired networks, the methods we already developed cover either the case of simple networks with a single node measurement or the case of complex networks with complete node measurements. Further developments are still necessary for intermediate situations.

In terms of applications, the use of electric cables as sensors for the monitoring of various structures is still at its beginning. We believe that this new technology has a strong potential in different fields, notably in civil engineering and in materials engineering.

3.4.3. PEGASE platform

A new iteration called PEGASE 2 of our wireless platform has to be finalized (see Software section), in particular:

- Validation of PEGASE 2 mother board for its ability to recover energy from solar cells. Writing resulting abacus and user-guides...
- Discover and manage the DSP Library of PEGASE 2 (TI 5330 processor)
- Finalizing its main daughter boards:
  - 8 synchronous analog channel daughter board (finalized at 90
  - validation of the POE (Power Over Ethernet) daughter board
  - validation of the 3G daughter board (for GSM links)
  - Finalizing the supervisor (Matlab plugin...)

3.4.4. Non Destructive testing of CFRP bonded on concrete through active thermography

Strengthening or retrofitting of reinforced concrete structures by externally bonded fibre-reinforced polymer (FRP) systems is now a commonly accepted and widespread technique. However, the use of bonding techniques always implies following rigorous installation procedures. The number of carbon fibre-reinforced polymer (CFRP) sheets and the glue layer thickness are designed by civil engineers to address strengthening objectives. Moreover, professional crews have to be trained accordingly in order to ensure the durability and

Figure 7. PEGASE board

long-term performance of the FRP reinforcements. Conformity checking through an ‘in situ’ verification of the bonded FRP systems is then highly desirable. The quality control programme should involve a set of adequate inspections and tests. Visual inspection and acoustic sounding (hammer tap) are commonly used to detect delaminations (disbonds). Nevertheless, these techniques are unable to provide sufficient information about the depth (in case of multilayered composite) and width of the disbonded areas. They are also incapable of evaluating the degree of adhesion between the FRP and the substrate (partial delamination, damage of the resin and poor mechanical properties of the resin). Consequently, rapid and efficient inspection methods are required. Among the non-destructive (NDT) methods currently under study, active infrared thermography is investigated due to its ability to be used in the field. In such context and to reach the aim of having an in situ efficient NDT method, we carried out experiments and subsequent data analysis using thermal excitation. Image processing, inverse thermal modelling and 3D numerical simulations are used and then applied to experimental data obtained in laboratory conditions.

3.4.5. IRSHM: Multi-Sensing system for outdoor thermal monitoring

Ageing of transport infrastructures combined with traffic and climatic solicitations contribute to the reduction of their performances. To address and quantify the resilience of civil engineering structure, investigations on robust, fast and efficient methods are required. Among research works carried out at IFSTTAR, methods for long term monitoring face an increasing demand. Such works take benefits of this last decade technological progresses in ICT domain.

Thanks to IFSTTAR years of experience in large scale civil engineering experiment, I4S is able to perform very long term thermal monitoring of structures exposed to environmental condition, as the solar heat flux, natural convection or seasonal perturbation. Informations system are developed to asses the data acquisition and researchers work on the quantification of the data to detect flaws emergence on structure, those techniques are also used to diagnose thermal insulation of buildings or monitoring of rail-roads, Figure 8 left. Experiments are carried out on a real transport infrastructure open to traffic and buildings. The detection of the inner structure of the deck is achieved by image processing techniques (as FFT), principal component thermography (PCT), Figure 8 right, or characterization of the inner structure thanks to an original thermal modelling approach.

For the next few years, I4S is actively implied in the SenseCity EQUIPEX (http://sense-city.ifsttar.fr/) where our informations systems are used to monitor a mini-city replica, Figure 9.

3.4.6. R5G: The 5th Generation Road

The road has to reinvent itself periodically in response to innovations, societal issues and rising user expectations. The 5th Generation Road (R5G) focuses firmly on the future and sets out to be automated, safe, sustainable and suited to travel needs. Several research teams are involved in work related to this flagship project for IFSTTAR, which is a stakeholder in the Forever Open Road. Through its partnership with the COSYS (IFSTTAR) department, I4S is fully implicated in the development of the 5th Generation Road.

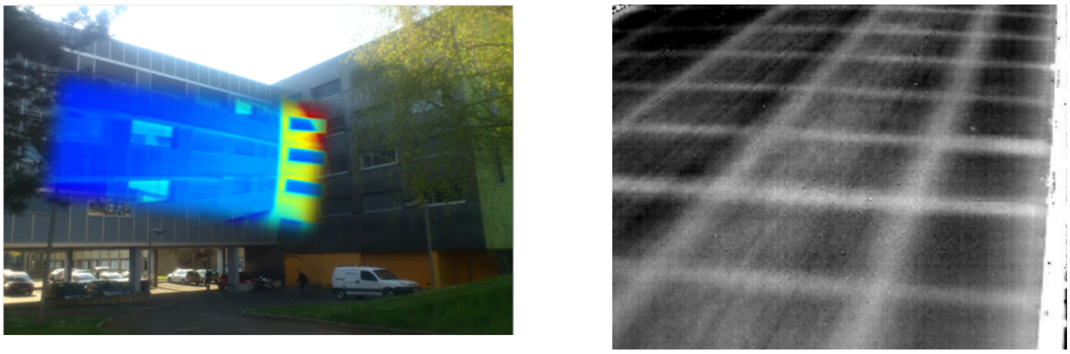

Figure 8. Left: Composite Data example which can be used on our research - Right: PCT result on a bridge deck

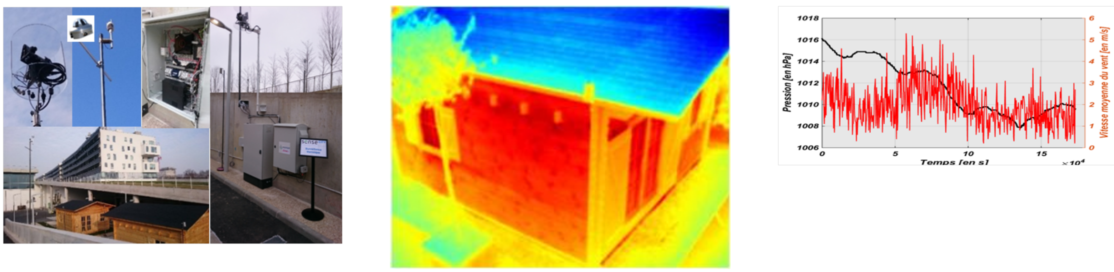

Figure 9. Various view and results of the SenseCity experimentation site - (site and hardware view, IR imaging, Environmental Monitoring)

Most of the innovations featured in R5G are now mature, for example communication and energy exchange between the infrastructure, the vehicle and the network manager; recyclable materials with the potential for self-diagnosis and repair, a pavement surface that remains permanently optimal irrespective of climatic variations... Nevertheless, implementing them on an industrial scale at a reasonable cost still represents a real challenge. Consultation with the stakeholders (researchers, industry, road network owners and users) has already established the priorities for the creation of full-scale demonstrators. The next stages are to achieve synergy between the technologies tested by the demonstrators, to manage the interfaces and get society to adopt R5G.

4. Application Domains

4.1. Civil Engineering

For at least three decades, monitoring the integrity of the civil infrastructure has been an active research topic because of major economical and societal issues, such as durability and safety of infrastructures, buildings and networks. Control of civil structures began a century ago. At stake is the mastering of the aging of the bridges, as in America (US, Canada) and Great Britain, or the resistance to seismic events and the protection of the cultural heritage, as in Italy and Greece. The research effort in France is very ancient since for example early developments of optical methods to monitor civil structures began in the 70s and SHM practice can be traced back to the 50s with the vibrating wire sensors as strain gauges for dams. Stille the number of sensors actually placed on civil structures is kept to a minimum, mainly for cost reasons, but also because the return on investment sensing and data processing technologies is not properly established for civil structures. One of the current thematic priorities of the C2D2 governmental initiative is devoted to construction monitoring and diagnostics. The picture in Asia (Japan, and also China) is somewhat different, in that recent or currently built bridges are equipped with hundreds if not thousands of sensors, in particular the Hong Kong-Shenzen Western Corridor and Stonecutter Bridge projects. However, the actual use of available data for operational purpose remains unclear.

Among the challenges for vibration-based bridges health monitoring, two major issues are the different kinds of (non measured) excitation sources and the environmental effects. Typically the traffic on *and* under the bridge, the wind and also the rain, contribute to excite the structure, and influence the measured dynamics. Moreover, the temperature is also known to affect the eigenfrequencies and mode-shapes, to an extent which can be significant w.r.t. the deviations to be monitored.

Thermomechanical prestress states affect the dynamic and the static behavior of most bridges, not only of very long and flexible ones. So, the reliable and fast determination of the state of prestress and prestrain associated with a temperature field becomes a crucial step in several engineering processes such as the health monitoring of civil structures. The best possible reconstruction of the temperature field could then become part of a complete process including massively distributed sensing of thermomechanical information on the structure, modeling and algorithms for the on-line detection of damages in the sense of abnormalities with regard to a nominal state, the whole chain being encapsulated in professional tools used by engineers in charge of real-life structural monitoring. For lack of an adequate mobilization of the useful multidisciplinary skills, this way remains about unexplored today.

4.2. Electrical cable and network monitoring

The fast development of electronic devices in modern engineering systems comes with more and more connections through cables, and consequently, the reliability of electric connections becomes a crucial issue. For example, in a modern automotive vehicle, the total length of onboard cables has tremendously increased during the last decades and is now up to 4km. These wires and connectors are subject to aging or degradation because of severe environmental conditions. In this area, reliability becomes a safety issue. In some other domains, cable defects may have catastrophic consequences. It is thus a crucial challenge to design smart embedded diagnosis systems able to detect wired connection defects in real time. This fact has motivated research projects on methods for fault diagnosis in electric transmission lines and wired networks. Original methods have been recently developed by Inria, notably based on the inverse scattering theory, for cable and network monitoring. Further developments concern both theoretic study and industrial applications.

4.3. Aeronautics

Improved safety and performance and reduced aircraft development and operating costs are major concerns in aeronautics industry. One critical design objective is to clear the aircraft from unstable aero-elastic vibrations (flutter) in all flight conditions. Opening of flight domain requires a careful exploration of the dynamical behavior of the structure subject to vibration and aero-servo-elastic forces. This is achieved via a combination of ground vibration tests and in flight tests. For both types of tests, various sensors data are recorded, and modal analyses are performed. Important challenges of the in-flight modal analyses are the limited choices for measured excitation inputs, and the presence of unmeasured natural excitation inputs (turbulence). Today, structural flight tests require controlled excitation by ailerons or other devices, stationary flight conditions (constant elevation and speed), and no turbulence. As a consequence, flight domain opening requires a lot of test flights and its costly. This is even worse for aircrafts having a large number of variants (business jets, military aircrafts). A key challenge is therefore to allow for exploiting more data under more conditions during flight tests: uncontrolled excitation, nonstationary conditions.

5. Highlights of the Year

5.1. Highlights of the Year

Paper [29]. was nominated for best paper at IFAC SAFEPROCESS in 2015.

A. Nassiopoulos is launching the startup Ecotropy from December 2015.

6. New Software and Platforms

6.1. Platform: PEGASE

Plate-forme Experte Générique pour Applications Sans-fil Embarquées
KEYWORD: SHM (Structural Health Monitoring)
SCIENTIFIC DESCRIPTION

I4S is actually finalizing the setup of a new platform named PEGASE 2.0 as the technological successor of the previous PEGASE platform developed by IFSTTAR.

The new version of PEGASE keeps the best of its previous version in its main vocation, to be a generic high level Wireless Sensor Platofrm.

What does not change between PEGASE 1 and 2.0: Based on various feedback from application fields, results from real structures monitored by PEGASE, and due to the rapid obsolescence of electronic devices, the design of the new PEGASE platform has been launched in 2013. Some of the main functions of PEGASE does not change but are reinforced.

Software genericity: use of a Linux embedded OS to make any application developed independently from the hardware, to make the user able to manage the system without ant physical and heavy operations.

Hardware genericity: with a principle of daughter and mother boards, each redundant need is embedded (processing, memory, timing, GPS, energy, etc) which each pluggable daughter board implements a specific function (sensing, 3G, Ethernet, communication, signal processing and relay control).

Accurate time synchronization: based on an original GPS and PPS algorithm, PEGASE platform is one of the only board able to time-stamp data from sensors or any event with an accuracy of some micro-seconds Universal Time.

What's new on PEGASE 2 platform ?

Previous principles are maintained or extended. Full electronic design from scratch occurred in 2014 to maximise its capacities in terms efficiency, cost, energy consumption, etc. Its main characteristics are

Important software evolutions: the platform embedded a real Linux kernel (not
FUNCTIONAL DESCRIPTION

I4S is actually finalizing the setup of a new platform named PEGASE 2.0 as the technological successor of the previous PEGASE platform developed by IFSTTAR.

The new version of PEGASE keeps the best of its previous version in its main vocation, to be a generic high level Wireless Sensor Platofrm.

What does not change between PEGASE 1 and 2.0: Based on various feedback from application fields, results from real structures monitored by PEGASE, and due to the rapid obsolescence of electronic devices, the design of the new PEGASE platform has been launched in 2013. Some of the main functions of PEGASE does not change but are reinforced.

Software genericity: use of a Linux embedded OS to make any application developed independently from the hardware, to make the user able to manage the system without ant physical and heavy operations.

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Accurate time synchronization: based on an original GPS and PPS algorithm, PEGASE platform is one of the only board able to time-stamp data from sensors or any event with an accuracy of some micro-seconds Universal Time.

- Participants: Vincent Le Cam, Mathieu Le Pen, Laurent Mevel and Michael Doehler
- Contact: Michael Doehler
- URL: http://www.a3ip.com/joomla/index.php?option=com_content&view=article&id=12&Itemid=8

6.2. TDISTL

Time domain inverse scattering for transmission lines
KEYWORDS: Transmission lines - Problem inverse - Fault diagnosis
SCIENTIFIC DESCRIPTION

TDISTL is a time domain variant of the previously developed frequency domain software ISTL for numerical computations of the inverse scattering transform applied to electrical transmission lines. It provides an efficient solution to experimentally determining the distributed characteristic impedance of electrical transmission line from the time domain reflectogram (impulse response) measured at one end of the line. Its current applications are in the fields of electrical cable fault diagnosis. It is registered at Agence pour la Protection des Programmes (APP) under the number IDDN.FR.001.250014.000.S.P.2015.000.30705.

FUNCTIONAL DESCRIPTION

Computation of the distributed characteristic impedance of a transmission line from time domain reflectometry measurement

- Participants: Qinghua Zhang and Michel Sorine
- Contact: Qinghua Zhang

6.3. Cloud2SM

Cloud architecture design for Structural Monitoring with in-line Sensors and Models tasking

KEYWORDS: SHM, online physical models, Data Management, Multi-physics Sensing, GPGPU acceleration
SCIENTIFIC DESCRIPTION

From the past decades the monitoring of civil engineering structure became a major field of research and development process in the domains of modelling and integrated instrumentation. This increasing of interest can be attributed in part to the need of controlling the aging of such structures and on the other hand to the need to optimize maintenance costs. From this standpoint the project Cloud2SM (inria ADT) has been launched to develop a robust information system able to assess the long term monitoring of civil engineering structures as well as interfacing various sensors and data. The specificity of such architecture is to be based on the notion of data processing through physical or statistical models. Thus the data processing, whether material or mathematical, can be seen here as a resource of the main architecture. The project can be divided in various items:

- The sensors and their measurement process: Those items provide data to the main architecture and can embed storage or computational resources. Dependent of onboard capacity and the amount of data generated it can be distinguished heavy and light sensors.
- The storage resources: Based on the cloud concept this resource can store at least two types of data, raw data and processed ones.
- The computational resources: This item includes embedded "pseudo real time" resources as the dedicated computer cluster or computational resources.
- The models: Used for the conversion of raw data to meaningful data. Those types of resources inform the system of their needs they can be seen as independents blocks of the system.
- The user interface: This item can be divided in various HMI to assess maintaining operation on the sensors or pop-up some information to the user.
- The demonstrators: The structures themselves.

Beside those objective, the I4S ADT campaign has allowed the development of the first block of the architecture: the data acquisition system. Called Cloud2IR, this prototype implementation of generic sensor interface has been specialized for the long term thermal monitoring of civil engineering structure and opened the way to the development of a whole ecosystem of sensors

6.3.1. Cloud2IR

Cloud 2IR is a software dedicated to the structural health monitoring of civil engineering structures thanks to long term thermal imaging. Its particularity lies in the fact that it is based on a generic approach of the acquisition system concept and the format of the data. That allow it to apply to other types of sensor. Information can be obtained on the inria bil, https://bil.inria.fr/fr/software/view/2536/tab.

7. New Results

7.1. Reflectometry

7.1.1. Experimental validation of the inverse scattering method for distributed characteristic impedance estimation

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Florent Loete (GEEPS-SUPELEC) and with Michel Sorine, formerly member of the Inria SISYPHE EPI.

Recently published theoretic results and numerical simulations have shown the ability of inverse scattering-based methods to diagnose soft faults in electric cables, in particular, faults implying smooth spatial variations of cable characteristic parameters. The purpose of the present work is to realize laboratory experiments confirming the ability of the inverse scattering method for retrieving spatially distributed characteristic impedance from reflectometry measurements. Various smooth or stepped spatial variations of characteristic impedance profiles are tested. This study has been accomplished in the framework of the ANR SODDA project and the results have been published in IEEE Transactions on Antennas and Propagation [16].

7.2. Automatic control

7.2.1. Observability conservation by output feedback and observability Gramian bounds

Participants: Qinghua Zhang, Liangquan Zhang.

Though it is a trivial fact that the observability of a linear state space system is conserved by output feedback, it requires a rigorous proof to generalize this result to uniform complete observability, which is defined with the observability Gramian. The purpose of this work is to complete such a proof. Some issues in existing results are also discussed. The uniform complete observability of closed loop systems is useful for the analysis of some adaptive systems and of the Kalman filter. This study has been accomplished in the framework of the ITEA MODRIO project and the results have been published in Automatica [19].

7.2.2. Weighted principal component analysis for Wiener system Identification: regularization and non-Gaussian excitations

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Vincent Laurain (CRAN/CNRS/Université de Lorraine) and with Jiandong Wang (Peking University).

Finite impulse response (FIR) Wiener systems driven by Gaussian inputs can be efficiently identified by a well-known correlation-based method, except those involving even static nonlinearities. To overcome this deficiency, another method based on weighted principal component analysis (wPCA) has been recently proposed. Like the correlation-based method, the wPCA is designed to estimate the linear dynamic subsystem of a Wiener system without assuming any parametric form of the nonlinearity. To enlarge the applicability of this method, it is shown in this work that high order FIR approximation of IIR Wiener systems can be efficiently estimated by controlling the variance of parameter estimates with regularization techniques. The case of non-Gaussian inputs is also studied by means of importance sampling. The results of this study have been presented in [21].

7.2.3. LPV system common state basis estimation from independent local LTI models

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Lennart Ljung (Linköping University).

For the identification of a linear parameter varying (LPV) system steered by a scheduling variable evolving within a finite set, the local approach consists in separately estimating local linear time invariant (LTI) models corresponding to fixed values of the scheduling variable. It is shown in this work that, without any global structural assumption of the considered LPV system, the local state-space LTI models do not contain the necessary information about the similarity transformations making them coherent. Nevertheless, it is possible to estimate these similarity transformations from input-output data under appropriate input excitation conditions. These estimations result in a common state basis of the transformed local LTI models, so that they form a coherent global LPV model, suitable for numerical simulations in the case of fast scheduling variable evolutions. This study has been accomplished in the framework of the ITEA MODRIO project and the results have been presented in [38].

7.3. Damage detection and linear state analysis

7.3.1. Vibration monitoring by eigenstructure change detection based on perturbation analysis

Participants: Michael Doehler, Qinghua Zhang, Laurent Mevel.

Vibration monitoring, notably in the fields of civil, mechanical and aeronautical engineering, aims at detecting damages at an early stage, in general by using output-only vibration measurements under ambient excitation. In this work, a new method is developed for the detection of small changes in the eigenstructure of such systems. The main idea is to transform the multiplicative eigenstructure change detection problem to an additive one, by means of perturbation analysis based on the assumption of small eigenstructure changes. Another transformation then further simplifies the detection problem into the framework of a linear regression subject to additive white Gaussian noises, leading to a numerically efficient solution of the considered problem. Compared to existing methods, it has the advantages of focusing on chosen system parameters and efficiently addressing random uncertainties. The results of this study have been presented in [30].

7.3.2. Stochastic hybrid system actuator fault diagnosis by adaptive estimation

Participant: Qinghua Zhang.

Based on the interacting multiple model (IMM) estimator for hybrid system state estimation and on the adaptive Kalman filter for time varying system joint state-parameter estimation, a new algorithm, the adaptive IMM estimator, is developed in this work for actuator fault diagnosis in stochastic hybrid systems. The working modes of the considered hybrid systems are described by stochastic state-space models, and the mode transitions are characterized by a Markov model. Actuator faults are modeled as parameter changes, and the related fault diagnosis problem is solved by the proposed adaptive IMM estimator through joint state-parameter estimation. This study has been accomplished in the framework of the ITEA MODRIO project and the results have been presented in [39].

7.3.3. Damage detection on real structures

Participants: Dominique Siegert, Laurent Mevel.

This article presents the feasibility study of a new structure for a 10-m-span bridge deck, taking into account the possibilities offered by new and high-strength materials and the advantages of a traditional environmental-friendly material. Small localized damages are hardly detected by global monitoring methods. The effectiveness of vibration-based detection depends on the accuracy of the modal parameter estimates and is limited by the low sensitivity of the modal parameters to a local stiffness reduction. This paper presents the application of SSDD to detect the change of the modal parameters of the investigated structure. Further analysis with a finite element model was conducted for assessing the consistency of the expected location and extent of the damaged elements. [15].

7.3.4. Damage detection and simulated validation

Participants: Michael Doehler, Laurent Mevel, Saeid Allahdadian.

This section is devoted to the numerical and theoretical validation of stochastic subspace damage detection. Sample length and sensor noise robustness were investigated. [23], [22], [24].

7.3.5. Damage quantification

Participants: Michael Doehler, Laurent Mevel.

Fault detection for structural health monitoring has been a topic of much research during the last decade. Localization and quantification of damages, which are linked to fault isolation, have proven to be more challenging, and at the same time of higher practical impact. While damage detection can be essentially handled as a data-driven approach, localization and quantification require a strong connection between data analysis and physical models. This paper builds upon a hypothesis test that checks if the mean of a Gaussian residual vector whose parameterization is linked to possible damage locations has become non-zero in the faulty state. It is shown how the damage location and extent can be inferred and robust numerical schemes for their estimation are derived based on QR decompositions and minmax approaches. Finally, the relevance of the approach is assessed in numerical simulations of two structures.[29].

7.3.6. Optical fiber for damage detection

Participant: Dominique Siegert.

A technique has been developed to detect and quantify structural damages. It consists of updating the model parameters associated to the damage, i.e. Young modulus, from strain sensor outputs obtained by optical fiber. Early damage detection can be expected using the local information given by the strain measurement. The method has been applied to a 8 meter post-tensioned concrete beam under a static loading. The model updating problem can be formulated as a minimization problem, i.e minimize a data misfit functional. To solve this problem, we use a gradient-based method. The gradient of the functional is computed at a low computational cost by means of the adjoint state. The technique is able to detect the damaged area in a post-tensioned concrete beam and to estimate its level of damage. [37]

7.4. Smarts roads and R5G

7.4.1. Positive surface temperature pavement

Participants: Jean Dumoulin, Nicolas Le Touz.

The mobility during winter season in France mainly relies on the use of de-icers, with an amount ranging from two hundreds thousands tons up to two millions tons for the roads only. Besides the economic impact, there are many concerns on their environmental and infrastructure, both on roads and on airports. In such context and in the framework of the R5G (5th Generation Road) project driven by IFSTTAR, investigations were carried out on the way to modify the infrastructure to maintain pavement surface at a temperature above water freezing point. Two distinct approaches, that can could be combined, were selected. The first one consisted in having a heated fluid circulating in a porous layer within an asphalt concrete pavement sample. The second one specifically relied on the use of paraffin phase change materials (PCM) in cement concrete pavement ones. Experiments on enhanced pavement samples were conducted in a climatic chamber to simulate winter conditions for several continuous days, including wind and precipitations, and monitored by infrared thermography. [45], [33]

7.4.2. Road structure design with energy harvesting capabilities

Participants: Nicolas Le Touz, Jean Dumoulin.

Facing the heavy organisational, financial and environmental constraints imposed by usual winter maintenance salting operations, pavement engineers have been led to look for alternative solutions to avoid ice or snow deposit at pavements surface. Among the solutions, one is self-de-icing heating pavements, for which two technologies have been developed so far: one is based on embedded coils circulating a heated calorific fluid under the pavement surface; the other one relies on the use of embedded resistant electric wires. The use and operation of such systems in the world is still limited and was only confined to small road stretches or specific applications, such as bridges which are particularly sensitive to frost. One of the most significant coil technology example in Europe is the SERSO-System (Solar Energy recovery from road surfaces) built in 1994, on a Switzerland bridge. Many of these experiences are referenced in the technical literature, which provides state-of-the art papers (see for instance Eugster) and useful detailed information dealing with the construction and operational management of such installation. The present study is taking part of the Forever Open Road Concept addressed by the R5G: 5th Generation Road , one of the major project supported by IFSTTAR. It considers a different design of self-de-icing road that simplify its mode of construction and maintenance, compared to the two technologies mentioned above. It should also be noted that similar to pavements instrumented with coils, such structure could be used in the reversible way to capture the solar energy at the pavement surface during sunny days and store it, to either warm the pavement at a later stage or for exogenous needs (e.g. contribution to domestic hot water). To complete our study we also considered the use of semi-transparent pavement course wearing in place of the traditional opaque one. In the present study, a 2D model was developed using FEM approach. It combines 2 numerical models. One is dedicated to the calculation of the heat transfer inside the porous layer between the fluid and the structure according to the geometry studied and the physical properties of the components of the system. The second one addresses the heat transfer inside the different layer of the pavement and was adapted to allow the insertion of a semi-transparent surface layer (for sun radiation). The temperature spatial distribution within the structure and its surface is calculated at different time step according to the evolution of boundary conditions at its surface. Various location in France were selected and calculation of the temperature field was carried-out over a year. Discussion on the performances of such system versus its location is proposed. Influence of a semi-transparent layer is also discussed. Future works will compared numerical simulations with experiments thank to a dedicated test bench under development and that will allow to test various structure in parallel. [31]

7.5. Non Destructive Testing using Infrared Thermography

7.5.1. Optimal designs of experience for thermal NDT

Participants: Antoine Crinière, Jean Dumoulin.

During previous works, square pulsed thermography was used to carry out non destructive testing of bonding quality of CFRP glued on civil engineering structures during reinforcement operations. The use of such wave form excitation was motivated by “on-site” requirements, but also by measurements duration, number of composite layers to test, depth of possible faulting areas versus temperature elevation allowed at composite level according to inner heat diffusion. Nevertheless, square pulsed excitation implies to choose an adapted heat duration. This duration is directly linked to the reliability of the parameter estimator. According to these observations, an indicator able to predict the sufficient heating time when the reliability of the parameter estimator reached an asymptotic evolution behaviour was studied. Based on the absolute thermal contrast, the proposed indicator Iph is defined with the maximum thermal contrast and the time delay between the heating time and the appearance of the maximum contrast. This indicator allows to take into account the detectability as well as the induced flaw temporal effect on the thermal contrast shape evolution. This paper will present the establishment of this indicator for optimal square heating time and present an analysis of results obtained with numerical simulations and laboratory experiments. [27]

7.5.2. Thermal NDT and signal processing

Participant: Jean Dumoulin.

This work deals with the detection of non-emergent small structures like mosaic, hidden under a plaster layer, with various spatial layout and nature. Three post processing approach by PPT, SVD and Polynomial analysis were conducted on this experimental and simulated data set. Results obtained are analysed and discussed. Finally, influence of IR camera used will be also addressed and discussed in the dissertation. [34]

7.6. Outdoor InfraRed Thermography

7.6.1. Vision enhancement through Infrared imaging for transport infrastructures

Participant: Jean Dumoulin.

Fog conditions are the cause of severe car accidents in European western countries because of the poor induced visibility. Its occurrence and intensity are still very difficult to forecast for weather services. Furthermore, visibility determination relies on expensive instruments and does not ease their dissemination. Lately, it has been demonstrated the benefit of infrared cameras to detect and to identify objects in fog while visibility is too low for eye detection. Over the past years, such cameras have become more cost effective. A research program between IFSTTAR and Cerema studied the possibility to retrieve visibility distance in a fog tunnel during its natural dissipation. The purpose of this work is to retrieve atmospheric visibility with a technique based on the combined use of infrared thermography, Principal Components Analysis (PCA) and Partial Least-Square (PLS) regression applied to infrared images.[44] and [17]

7.6.2. Outdoor thermal monitoring of large scale structures by infrared thermography

Participants: Jean Dumoulin, Antoine Crinière.

With the constant increase of the road traffic coupled with the ageing of transport infrastructure, studying and developing robust system which allows to monitor and assess those structures is of growing interest. Among the techniques used [1], thermal monitoring with infrared thermography appears to be a good compromise between a non-intrusive method and possible added value after post-processing of acquired data. Through the past decade studies have shown the ability to monitor concrete and asphalt structure by active IR thermography. On site measurement using passive thermography have also been studied, by applying qualitative methods and quantitative one. These methods have been used to perform punctual control of various duration (few hours to few days). However, infrared thermography, when it is used in a quantitative mode (not in laboratory conditions) and not in a qualitative mode (vision applied to survey), needs to process thermal radiative corrections on the raw data acquired in real time, to take into account the influences of the natural environment's evolution with time. The ICT system called "IrLaW" is based on a multi sensing approach. It connects and synchronizes information acquired by a weather station, a GPS and an infrared camera. To fulfill ICT objectives (OGCcompliant), a specific hardware architecture was also designed and studied to allow the whole system integration in a TCP/IP network. [28]

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. PhD CIFRE with EDF

Participants: Nassif Berrabah, Qinghua Zhang.

A joint PhD project between Inria and EDF (Electricité de France) has been started since December 2014. The purpose of this study is to develop methods for the monitoring of electrical instruments in power stations, in order to prevent failures caused by aging or accidental events. This project is funded by EDF and by the ANRT agency for three years.

8.1.2. Contracts with SVS

Participants: Laurent Mevel, Michael Doehler.

Annual agreement Inria-SVS 2381 + contract 4329

I4S is doing technology transfer towards SVS to implement I4S technologies into ARTEMIS Extractor Pro. This is done under a royalty agreement between Inria and SVS .

In 2014, the damage detection toolbox has been launched http://www.svibs.com/products/ARTeMIS_Modal_Features/Damage_Detection.aspx.

In 2015, SVS and Inria have earned an Innobooster grant to help transfer algorithms in 2016 Artemis Extractor Pro.

8.1.3. Contracts with A3IP

Participant: Vincent Le Cam.

A licensing work has been initialized at IFSTTAR in order to sold some licenses of PEGASE 2 to companies who would like to use, modify, extend and sell the functions in the Structural Health Monitoring world. Separate and non-exclusive licenses will be regarded to:

- a) sell the PEGASE 2 devices : mother and daughter boards
- b) sell the PEGASE 2 Supervisor

8.1.4. Contract with SNCF : DEMETER

Participants: Vincent Le Cam, Mathieu Le Pen.

Deployment of a set of PEGASE platform for SNCF: SNCF has just signed a contract in view of instrumenting 2 railways sites where the needs of wireless and smart sensors has been expressed. The overall objective is to evaluate the contribution of intelligent and autonomous sensors in rail uses-boxes. I4S next contribution will mainly focus on data processing and algorithms implementation.

8.1.5. Collaboration with SNCF

Participant: Jean Dumoulin.

SNCF as contacted us to assess the thermal monitoring of some of their railways walls.

8.1.6. Contract with GDF

Participants: Vincent Le Cam, Mathieu Le Pen.

GDF (national french Gaz company) has signed a wide contract with IFSTTAR relative to many items in Wireless Sensors Networks. One of the items will be prototyped on PEGASE 2 platform and consists in finding an accurate solution for WSN synchronization without GPS source and for an autonomy of 10 years. One of the identified solution will be prototyped on PEGASE 2 as wireless and generic development platform and as it offers an accurate 100 nanoseconds absolute time reference.

8.1.7. Collaboration with SIEMENS : NEOVAL Rennes

Participant: Jean Dumoulin.

Since 2012, a work has been initiated for thermal studies for SIEMENS about subway infrastructures. 2013 was dedicated to the study of thermal instrumentation of subway. 2014 was focused on the instrumentation of a rail mockup in Nantes.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. MAG2C-Pont Tabarly

Participant: Ivan Guéguen.

Type: GIS

Objectif: bridge instrumentation

Duration: Since 2014

Coordinator : LIRGEC

Partners: IFSTTAR, CSTB, Nantes Métropole, Université de Nantes

Inria contact: Ivan Guéguen

Abstract: The project deals with the instrumentation of the Tabarly Bridge.

The instrumentation auscultates globally the structure, a structural defect in a given location changes its modal parameters and thus the vibration behavior. Then it can be detected on any part of the structure with an accelerometer. These measures coupled with a wireless data transmission system type or wifi 3g will allow remote monitoring of the evolution of the structure. And where appropriate, to deploy when necessary, for maintenance. The different objectives are

- Experimentation on a bridge
- Equipment qualification in real conditions over the long term
- Apply different vibration processing algorithms
- Surveillance and Detection
- Measurement database

The instrument proposed is based on an accelerometer-based distributed network on the structure. This assembly is connected to a data acquisition system and a modem 3g for continuous measurements and remotely. The vibration will be collectable on the internet.

9.1.2. Project wind turbine in St Hilaire de Chaleon

Participant: Ivan Guéguen.

Type: GIS

Objectif: bridge instrumentation

Duration: Since 2014

Coordinator : LIRGEC

Partners: IFSTTAR

Inria contact: Ivan Guéguen

Abstract: The project deals with the instrumentation of the wind turbine.

The aim is firstly, to instrument the foundation before casting with continuous optical fibers, optical strain gauges, temperature sensors and accelerometers for a detailed analysis of the behavior of the founding quasi static and dynamic. In a second time to instrument the mast with accelerometers to the study by SSI under ambient vibration method. All of which should help better understand the global behavior of the structure.

9.1.3. Collaboration with GEM

Participants: Laurent Mevel, Michael Doehler, Md Delwar Hossain Bhuyan.

Md Delwar Hossain Bhuyan has started a PhD on Damage localisation on offshore platforms, The thesis is co-directed by L. Mevel and F. Schoefs from GEM, Nantes, with supervision shared with M. Doehler and Y. Lecieux from GEM. It is funded by the Brittany region for 3 years.

9.2. National Initiatives

9.2.1. High speed rail track Instrumentation

Participant: Ivan Guéguen.

Type: IRT

Objectif: bridge SHM

Duration: 11/2014 to 11/2018

Coordinator: RAILENIUM

Partners : IFSTTAR, EIFFAGE, RFF, LGCgE

Inria contact: Ivan Guéguen

Abstract: This project aims to orchestrate multiple sections of a high-speed route (classical section with granular layer, transition zone). The proposed instrumentation concerns all the different layers of the structure, and is designed to allow monitoring of the overall track behavior

The instrumentation will include: A Weather station measures environmental conditions (temperature, precipitation on the site). Accelerometers, to monitor the dynamic behavior of the track, with measures at several levels: the hammer beams on top of the grave-bitumen layer, on top of the soil. These measures will include acceleration compare the dynamic response of a section with and without GB. Instrumentation of severe bitumen strain gauges for measuring the longitudinal and transverse tensile strains at the base of the UK, and temperature probes (top and bottom layer). This instrumentation will estimate the fatigue life of the GB, temperature changes in this layer, and will calculate a temperature equivalent to the layer of GB. Instrumentation subgrade by means of measurement gauges at the top of the vertical deformation of the soil, and TDR probes to measure changes in water content. Its objective is to measure the levels of distortion in the upper part of the soil, and their variations, in conjunction with the seasonal variations in water content. An anchored sensor, measuring the total deflection between the top of the GB and a reference point that is 4 m deep. This sensor will measure the total displacement of the structure beneath the ballast (GB + layer of granular soil leveling + support). These will also serve as a reference for comparison with the movements deducted from accelerometer measurements. Continuous optical fiber, to measure static permanent deformation in the transverse direction over the entire width of the structure at the base of the sub-layer. These optical fibers used to monitor deformation obtained following the transverse profile in the game with underlay in the UK (in ballast) and the part with underlay GNT (Differential settlement, appearance of a crack ...).

9.2.2. REPTILES

Participant: Jean Dumoulin.

Type: FUI

Objectif: Innovation for rehabilitation of potable water tubes

Duration: Since 11/2012

Coordinator: FREYSSINET

Inria contact: J. Dumoulin

Since 2012, within FUI Reptiles, J. Dumoulin was coordinator of the conception, study and development of a thermoplastic composite assembly system for water tubes reenforcement. Moreover, infrared thermography was used for active control. [36]

9.2.3. Equipex Sense-City

Participants: Jean Dumoulin, Laurent Mevel, Antoine Crinière.

Through the ADT Cloud2SM, participation of I4S in SenseCity was possible. IFSTTAR's SensorBox developed by Jean Dumoulin was installed and presented at SEnseCity Kick off and is installed on-site. Cloud2IR and Cloud2SM software have been deployed within the ADT of A. Crinière. [42], [26] (http://sense-city.ifsttar.fr/)

9.3. European Initiatives

9.3.1. FP7 & H2020 Projects

9.3.1.1. Built to Specifications (Built2Spec)

Participants: Jean Dumoulin, Alexandre Nassiopoulos, Jordan Brouns.

Type: Horizon 2020

Defi: Model Driven Physical Systems Operation

Objectif: Reduce the gap between a building's designed and as-built energy performance.

Duration: January 2015 to January 2019

Coordinator: Manager and project head : NOBATEK, Germain Adell. For CERMA : Marjorie Musy

Inria teams I4S

Inria contact: J. Dumoulin

Partners: Consortium of 20 Public and Industrial actors

Website: http://built2spec-project.eu/

Abstract: Built to Specifications (Built2Spec) is a Horizon 2020 EU-funded project involving 20 European partners that seeks to reduce the gap between a building's designed and as-built energy performance. To do this, the project will put a new set of breakthrough technological advances for self-inspection checks and quality assurance measures into the hands of construction professionals. This collection of smart tools will help building stakeholders at all levels in meeting EU energy efficiency targets, new build standards and related policy goals.
Built2Spec will deliver a new set of tools:

- 3D and Imagery Tools
- Building Information Modelling (BIM)
- Smart Building Components
- Energy Efficiency Quality Checks
- Indoor Air Quality Tools
- Airtightness Test Tools with Air-pulse Checks
- Thermal Imaging Tools
- Acoustic Tools

All connected to a Virtual Construction Management Platform supporting the collection and sharing of all project data, from initial design to the delivery. During the project, this platform will be integrated into the operations of small and medium-sized enterprise (SME) contractors, large construction firms and end user clients directly within the consortium and work program activities, assuring systematic and scientific performance measures, feedback and powerful exploitation.

9.3.2. Collaborations in European Programs, except FP7 & H2020

9.3.2.1. Collaboration with BAM, Berlin

Participants: Laurent Mevel, Michael Doehler, Eva Viefhues.

Eva Viefhues is currently student in BAM, Berlin. a PhD will start in 2016. Michael Doehler has visited a few times BAM in 2015 to prepare and plan the PhD.

9.3.2.2. Collaboration with CNR-IREA, Italy

Participants: Jean Dumoulin, Nicolas Le Touz.

This internship aims to identify defects in the interior walls, using thermal and electromagnetic reconstruction method, developed by IFSTTAR (in Bouguenais) for thermal and CNR-IREA (in Naples) for electromagnetism.

First, we make a numerical study for the two direct problems, with the resolution of the heat equation with finite elements, allowing a detailed study of how is made the assembly of matrices for a problem in two or three dimensions. A study of Maxwell's equations solving by using a centered finite difference method is also conducted for the direct problem of electromagnetism.

We also study the resolution of these inverse problems, in particular with the calculation of a functional gradient using the adjoint method for the thermal reconstruction, what allows the resolution of the problem with the Levenberg-Marquardt algorithm, and a study of the Born model for the electromagnetism problem.

Applications to the reconstructions of various types of defects are then lead. These different situations allow to highlight the stimuli, thermal of electrical, to bring to the system so that the reconstruction is made correctly. We could thus reconstruct defects in domains of various dimensions with thermal or electromagnetism highlighting the electrical (conductivity, permittivity and permeability), thermal (effusivity) and mathematical parameters (regularization terms) playing on the fidelity of the reconstruction.

A coupling of these two reconstruction methods is then carried out to improve the fidelity of the reconstructions realized with only one of these two methods. In the case of this coupling, the reconstruction get with GPR data provides a priori information to the thermal inverse problem allowing to get a better location of the defects.

9.3.2.3. European Research Network on System Identification (ERNSI)

Participants: Qinghua Zhang, Michael Doehler, Laurent Mevel.

The I4S project-team is involved in the activities of the European Research Network on System Identification (ERNSI) federating major European research teams on system identification. Modeling of dynamical systems is fundamental in almost all disciplines of science and engineering, ranging from life science to process control. System identification concerns the construction, estimation and validation of mathematical models of dynamical physical or engineering phenomena from experimental data.

9.3.2.4. MODRIO

Participants: Qinghua Zhang, Liangquan Zhang.

Type: ITEA2

Defi: Model Driven Physical Systems Operation

Objectif: To meet the evermore stringent safety and environmental regulations for power plants and transportation vehicles, system operators need new techniques to improve system diagnosis and operation.

Duration: June 2012 to November 2015

Coordinator: Daniel Bouskela (EDF)

Inria teams PARKAS, HYCOMS, I4S

Inria contact: B. Caillaud

Abstract: Open standards are necessary for different teams to cooperate by sharing compatible information and data. To meet the evermore stringent safety and environmental regulations for power plants and transportation vehicles, system operators need new techniques to improve system diagnosis and operation. Open standards are necessary for different teams to cooperate by sharing compatible information and data. The objective of the MODRIO project is to extend modeling and simulation tools based on open standards from system design to system diagnosis and operation. This project joined by partners from Austria, Belgium, Finland, France, Germany, Italy and Sweden has been selected by the board of Information Technology for European Advancement (ITEA 2). The involved Inria project-teams are PARKAS, HYCOMES and I4S. This project is funded from June 2012 to November 2015.

9.3.2.5. COST Action TU 1402

Participants: Michael Doehler, Laurent Mevel.

L. Mevel is member of the management committee of the COST Action.

M. Doehler is co-leader of working group 2 "SHM technologies and structural performance".

Type: COST

Objectif: Quantifying the value of structural health monitoring

Duration: 11/2014 - 11/2018

Coordinator: S. Thoens (DTU Denmark)

Partner: 23 countries, see http://www.cost.eu/COST_Actions/tud/Actions/TU1402

Inria contact: Laurent Mevel

Abstract: This COST Action enhances the benefit of Structural Health Monitoring (SHM) by novel utilization of applied decision analysis on how to assess the value of SHM - even before it is implemented. This improves decision basis for design, operation and life-cycle integrity management of structures and facilitates more cost efficient, reliable and safe strategies for maintaining and developing the built environment to the benefit of society. SHM is increasingly applied for collecting information on loads and aggressive environments acting on structures, structural performances, deterioration processes and changes in the use of structures. However, there is an urgent need to establish a better understanding of the value of SHM before its implementation, together with practically applicable methods and tools for its quantification. This Action thus aims to develop and describe a theoretical framework, together with methods, tools, guidelines, examples and educational activities, for the quantification of the value of SHM. The COST Action will be conducted with the support of the Joint Committee on Structural Safety (JCSS). The networks of researchers and industries established during COST Actions TU0601, C26, E55 and E24, the EU FP7 project IRIS, the Marie Curie Network SmartEn and the JCSS will ensure visibility, impact and dissemination.

9.4. International Initiatives

9.4.1. Collaboration with British Columbia University, Canada

Participants: Laurent Mevel, Michael Doehler, Saeid Allahdadian.

Saeid Allahdadian is currently PhD student of professor Carlos Ventura in Vancouver. Following our recent papers, Michael Doehler has been invited to co-supervise the PhD of Saeid Allahdadian starting in 2016 for 3 years.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

S. Allahdadian from British Columbia University has visited us for a week in 2015.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific events organisation

10.1.1.1. Member of the organizing committees

Q. Zhang is member of the national organization committee of the IFAC Symposium SAFEPROCESS 2015.

10.1.2. Scientific events selection

10.1.2.1. Chair of conference program committees

V. Le Cam is head of of the scientific committee of the EWSHM scientific committee for 2015.

10.1.2.2. Member of the conference program committees

V. Le Cam was member of the scientific committee for IWSHM 2015 in Stanford.
J.Dumoulin is

- member of the scientific committee of the GI Division (Geosciences Instrumentation and Data Systems) of EGU for infrastructure instrumentation and monitoring since April 2013.
- member of the committee of QIRT (quantitative Infrared Thermography) since February 2014 (http://qirtasia2015.com/)
- organizer of some invited sessions at EGU 2015 (http://www.egu2015.eu/).

L. Mevel

- is member of the EWSHM scientific committee.
- is member of the IOMAC scientific committee.

Q. Zhang is

- Member of IFAC Technical Committee on Modelling, Identification and Signal Processing (TC 1.1, http://tc.ifac-control.org/6/4/).
- Member of IFAC Technical Committee on Fault Detection, Supervision and Safety of Technical Processes (TC 6.4, http://tc.ifac-control.org/6/4/).
- Member of the international program committee of the IFAC Symposium SYSID 2015.
- Member of the international program committee of the IFAC Symposium SAFEPROCESS 2015.

10.1.2.3. Reviewer

V. Le Cam was reviewer and session chairman for the IWSHM 2015 in Stanford

M. Doehler was reviewer for IFAC Safeprocess 2015 and IEEE Multi-Conference on Systems and Control

M. Doehler was co-chairman at SYSID 2015.

L. Mevel was reviewer and session chairman for IFAC Safeprocess 2015.

10.1.3. Journal

10.1.3.1. member of the editorial board

L. Mevel is member of the editorial board of journal of Mathematical Problems in Engineering.

L. Mevel is member of the editorial board of journal of Shock and Vibration.

Q. Zhang is member of the editorial board of the journal “Intelligent Industrial Systems”, Springer.

10.1.3.2. Reviewer - Reviewing activities

L. Mevel was reviewer for Mechanical Systems and Signal Processing, journal of Sound And Vibration. He was reviewer for Research Foundation Flanders in 2015.

M. Doehler was reviewer for Journal of Sound and Vibration, Sensors, Mechanical Systems and Signal Processing, Journal of Selected Topics in Signal Processing, Structural Control and Health Monitoring, ASCE Journal of Aerospace Engineering, ASCE Journal of Bridge Engineering, European Journal of Environmental and Civil Engineering

J. Dumoulin was reviewer for IEEE Transactions on Instrumentation and Measurement, Quantitative Infrared Thermography Journal, Optics and Lasers in Engineering journal , Journal Cultural Heritage, International Journal of Architectural Heritage, Journal of Geophysics and Engineering, Research in Nondestructive Evaluation

10.1.4. Invited talks

Q. Zhang was invited paper speaker at SYSID 2015 [21].

J. Dumoulin wa invited keynote speaker at QIRT’2015 [20].

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence Professionnelle TAM : J. Dumoulin, thermographie infrarouge active, 8h, Université Paris-Est, France

Master 2 MMMRI, (Maintenance et Maîtrise des Risques Industriels) , J. Dumoulin, contrôle non destructif par thermographie infrarouge active, 12h, Université Paris-Est, France

Master Système Communicant Mobile, V. Le Cam, embedded systems under Linux Operating System, 12h, Polytech Nantes, France

Master Civil engineering, V. Le Cam, Structural Monitoring, 4h, Université de Nantes, France

Licence 3 SEICOM, V. Le Cam, 3h, SHM and smart grids, Université de Nantes, France

Licence 3 SEICOM, V. Le Cam, 8h, TP, SHM and smart grids, Université de Nantes, France

ESEO, V. Le Cam, 8h, TP, embedded systems under Linux Operating System, France

10.2.2. Supervision

PhD : Delwar Hossain Bhuyan, *Damage localisation on offshore platforms*, L. Mevel and M. Doehler, Ecole doctorale MATISSE, Université de Rennes 1, since November 2014

Liangquan Zhang's post-doctoral project on hybrid system monitoring, Q. Zhang, 2014-2015.

Guillaume Gautier's post-doctoral project on morphosense system monitoring, L. Mevel, 2015-2017.

PhD : Nassif Berrabah, Electrical cable aging monitoring , Q. Zhang, Ecole doctorale MATISSE, Université de Rennes 1, since November 2014

J. Dumoulin was supervisor of the Master training of Nicolas Le Touz at Ecole Centrale Nantes (ECN) in 2014 and 2015.

10.2.3. Juries

- L. Mevel was referee for the PhD of Fatima Nasser at GIPSA Lab in May 2015.
- L. Mevel was referee for the PhD of Guillaume Gautier at INSA Val de Loire in July 2015.
- J. Dumoulin was part of the jury for María Inmaculada Martínez Garrido at E.T.S.Ingeniería y Sistemas de Telecomunicacíón de la Universidad Politécnica de Madrid in June 2015.

10.3. Popularization

- V. Le Cam has been invited at the ConfLunch of IRISA on April 24th 2015. http://videos.rennes.inria.fr/confLunch/#Le Cam.
- J. Dumoulin has been involved in the COP 21 France stand for a solar hybrid road demonstration.
- V. Le Cam was present at the inauguration of Cité des Objets Connectés in Angers on 11/06/15 in presence of France president. He was inside the Smart sensors stand for IFSTTAR.
- A nice showcase of I4S was present at the 2015's Hanover messe, in April 2015: BAM (Berlin) had a steel frame demonstrator for the public using our techniques.

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