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Activity Report 2016

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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1. Members

Research Scientists

Laurent Mevel [Team leader, Inria, Senior Researcher, HDR]
Michael Doehler [Inria, Researcher]
Jean Dumoulin [IFSTTAR, Researcher]
Dominique Siegert [IFSTTAR, Researcher, until Dec 2016]
Xavier Chapeleau [IFSTTAR, Researcher, since January 2016]
Qinghua Zhang [Inria, Senior Researcher, HDR]

Engineers

Antoine Crinière [Inria]

Ivan Guéguen [IFSTTAR]
Vincent Le Cam [IFSTTAR, Senior Engineer]
Mathieu Le Pen [IFSTTAR]

PhD Students

Nassif Berrabah [EDF, granted by CIFRE]
Md Delwar Hossain Bhuyan [Inria, granted by ARED Bretagne]
Nicolas Le Touz [IFSTTAR]
Thibaud Toullier [Inria, from Oct 2016, granted by ARED Bretagne]
Eva Viefhues [BAM, from Sep 2016]
Saeid Allahdadian [UBC, from Sep 2016]
Antoine Bassil [IFSTTAR, from Nov 2016]

Post-Doctoral Fellows

Jordan Brouns [IFSTTAR, until Mar 2016]
Guillaume Gautier [CEA]
Subhamoy Sen [Inria, from Nov 2016]

Other

Youssef Elkamali [Inria,Student,from Apr 2016 until Jul 2016]

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 reflectometry-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,

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

where V_n and W_n are zero mean random variables, 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, 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 classical mechanical equation (2)

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

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 priori 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 Rafik Zouari's PhD thesis for handling the aeroelastic effect.

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 :

$$\left\{ \begin{array}{rcl} X_{k+1} & = & F\; X_k + V_{k+1} \\ Y_k & = & H\; X_k + W_k \end{array} \right. , \tag{4}$$

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 :

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

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 [54].

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

$$\mathcal{H}_{p+1,q} \triangleq \begin{pmatrix} R_1 & R_2 & \vdots & R_q \\ R_2 & R_3 & \vdots & R_{q+1} \\ \vdots & \vdots & \vdots & \vdots \\ R_{p+1} & R_{p+2} & \vdots & R_{p+q} \end{pmatrix} \triangleq \mathrm{Hank}\,(R_i) \tag{7}$$

be the output covariance and Hankel matrices, respectively; and: $G \triangleq \mathbf{E}\left(X_k Y_{k-1}^T\right)$. Direct computations of the R_i's from the equations (4) lead to the well known key factorizations :

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

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 $\Delta \stackrel{\Delta}{=} \mathrm{diag}(\Lambda)$, 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:

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

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 $\widehat{\mathcal{H}}_{p+1,q}$:

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

and to define the residual vector:

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

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 [48] 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 [47].

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 $\mathfrak{J}_{\Phi\theta}$.

3.2. Thermal methods

3.2.1. Infrared thermography and heat transfer

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 $0.2\ \mu m$ and $1\ mm$, this range begin in uv spectrum and it ends on the microwaves domain, see Figure 1.

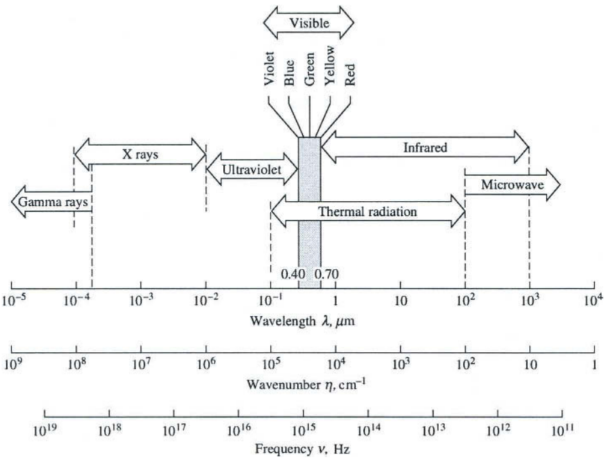

Figure 1. Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

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 \ 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 emitter 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 W.m^2 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 is the link between the photons energy and their frequency.

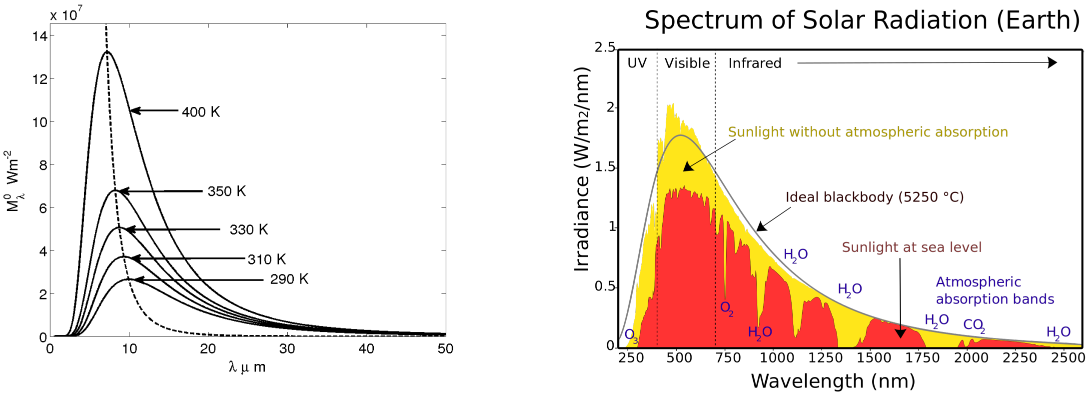

Figure 2. Left: Plank's law at various temperatures - Right: Energy spectrum of the atmosphere

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 is 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.

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.

3.2.1.2. Infrared Thermography

The infrared thermography is a way to measure the thermal radiation received from a medium. With that information about the electromagnetic flux it is possible to estimate the surface temperature of the body, see section 3.2.1.1. Various types of detector can assure the measure of the electromagnetic radiation.

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).

This field of activity includes the use and the improvement of vision system, like in [3].

3.2.2. Heat transfer theory

Once the acquisition process is done, it is 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 (22).

$$\varphi = k\nabla T \quad X \in \Omega \tag{22}$$

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 (23). This equation has been proposed by Joseph Fourier in 1811.

$$\rho C \frac{\partial T(X,t)}{\partial t} = \nabla \cdot (k\nabla T) + P \quad X \in \Omega \tag{23}$$

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 (23), it is 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 is possible, for example, to express the thermal radiation and the convection phenomenon which can occur at $\partial\Omega$ the system boundaries, cf Equation (24).

$$\varphi = k\nabla T \cdot n = \underbrace{h\left(T_{fluid} - T_{Boundarie}\right)}_{\text{Convection}} + \underbrace{\epsilon\sigma_s\left(T^4_{environement} - T^4_{Boundary}\right)}_{\text{Radiation}} + \varphi_0 \quad X \in \partial\Omega \tag{24}$$

Equation (24) 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 is 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 (25). For example if A represents the heat transfer, b can be the temperature evolution.

$$AP = b \tag{25}$$

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 (26).

$$P = A^{-1}b \tag{26}$$

Here we want find the solution AP which is closest to the acquired measures M, Equation (27).

$$AP \approx \mathcal{M} \tag{27}$$

To do that it is 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 is why we dont solve directly the system (27) but we minimise the quadratic coast function (28) which represents the Legendre-Gauss least square algorithm for linear problems.

$$min_P \left(\|AP - \mathcal{M}\|^2 \right) = min_P \left(\mathcal{F} \right) \tag{28}$$

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

$$\mathcal{F} = [AP - \mathcal{M}]^T [AP - \mathcal{M}] \tag{29}$$

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 (30) and find where it is equal to zero.

$$\nabla\mathcal{F}(P) = 2 \left[-\frac{\partial AP^T}{\partial P} \right] [AP - \mathcal{M}] = 2J(P)^T [AP - \mathcal{M}] \tag{30}$$

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 is the case when you want to estimate the external heat flux, φ_0 in equation 24. 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 (31).

$$P^{k+1} = P^k + \left[\left(J^k\right)^T J^k + \mu^k \Omega^k \right]^{-1} \left(J^k\right)^T \left[\mathcal{M} - A(P^k) \right] \tag{31}$$

Equation (31) is solved iteratively at each loop k. Some of our results with such linear or non linear method can be seen in [4] or [2], more specifically [1] is a custom implementation of the Levenberg-Marquardt algorithm based on the adjoint 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 ageing 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. 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.

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], [53]. It provides an efficient solution for the diagnosis of *soft* faults in electrical cables, like in the example illustrated in Figure 3. While most reflectometry methods for fault diagnosis are based on the detection and localization 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 [55], [51]. 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.

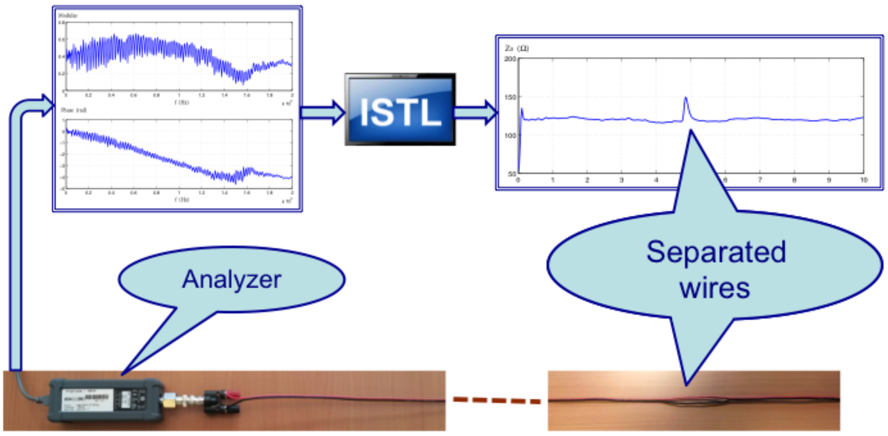

Figure 3. Inverse scattering software (ISTL) for cable soft fault diagnosis.

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.

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 [52]

$$\begin{aligned}\frac{\partial}{\partial z}V(t,z)+L(z)\frac{\partial}{\partial t}I(t,z)+R(z)I(t,z)=0\\ \frac{\partial}{\partial z}I(t,z)+C(z)\frac{\partial}{\partial t}V(t,z)+G(z)V(t,z)=0\end{aligned} \tag{32}$$

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

$$V(t,a)=V_s(t)-R_sI(t,a). \tag{33}$$

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

$$V(t,b) \quad = R_LI(t,b). \tag{34}$$

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 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 (32).

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 (32), whereas at each node the current and voltage satisfy the Kirchhoff's laws, unless in case of connector failures.

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 [50]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [49]. After having completed some theoretic results directly linked to practice [14], [53], we started to successfully apply the inverse scattering theory to cable soft fault diagnosis, in collaboration with GEEPS-SUPELEC [11].

To link electric cables to the inverse scattering theory, the telegrapher's equations (32) 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 (32) 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

$$\begin{aligned}\nu_1(\omega,x)=\frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega,x)-Z_0^{\frac{1}{2}}(x)I(\omega,x)\right]\\ \nu_2(\omega,x)=\frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega,x)+Z_0^{\frac{1}{2}}(x)I(\omega,x)\right]\end{aligned} \tag{35}$$

with

$$Z_0(x) = \sqrt{\frac{L(x)}{C(x)}}. \tag{36}$$

These transformations lead to the Zakharov-Shabat equations

$$\begin{aligned}\frac{d\nu_1(\omega,x)}{dx} + ik\nu_1(\omega,x) &= q^*(x)\nu_1(\omega,x) + q^+(x)\nu_2(\omega,x)\\ \frac{d\nu_2(\omega,x)}{dx} - ik\nu_2(\omega,x) &= q^-(x)\nu_1(\omega,x) - q^*(x)\nu_2(\omega,x)\end{aligned} \tag{37}$$

with

$$\begin{aligned}q^{\pm}(x) &= -\frac{1}{4}\frac{d}{dx}\left[ln\frac{L(x)}{C(x)}\right] \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right]\\ &= -\frac{1}{2Z_0(x)}\frac{d}{dx}Z_0(x) \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right]\\ q^*(x) &= \frac{1}{2}\left[\frac{R(x)}{L(x)} + \frac{G(x)}{C(x)}\right].\end{aligned} \tag{38}$$

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 (36), often known as the characteristic impedance, from the reflection coefficient measured at one end of the cable. Such an example is illustrated in Figure 3. Any fault affecting the characteristic impedance, like in the example of Figure 3 caused by a slight geometric deformation, can thus be efficiently detected, localized 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. The first method we developed for the diagnosis of such losses had some numerical stability problems. The new method [46], [26] is much more reliable and efficient. 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. 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 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.

3.4.4. 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 guided transport infrastructures, Figure 4 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 4 right, or characterization of the inner structure thanks to an original image processing approach.

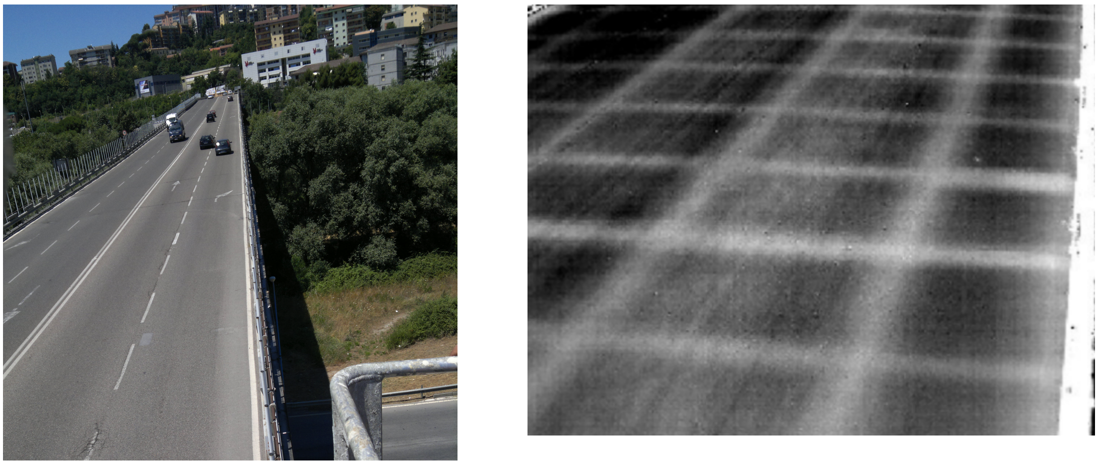

Figure 4. Left: Image in the visible spectrum of the deck surface - Right: PCT result on a bridge deck

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 5.

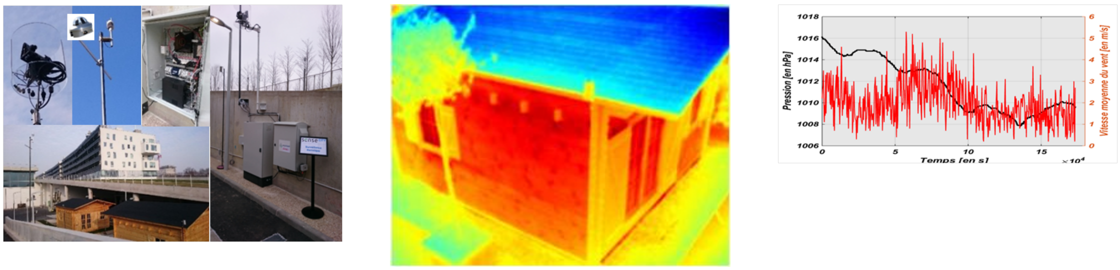

Figure 5. Various view and results of the SenseCity experimentation site - (site and hardware view, IR imaging, Environmental Monitoring)

3.4.5. 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.

Most of the innovations featured in R5G are now mature, for example communication and few solutions for 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 ageing 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 ageing 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

- In 2016, uncertainty quantification for modal analysis has been transferred to ARTeMIS software http://www.svibs.com/newsletter/newsletter_2016_09.aspx.
- In 2016, a patent has been filed by N. Berrabah and Q. Zhang, jointly with EDF and Inria [46].

- PEDAL-LORA monitoring sensor has been awarded by the European Railway Cluster Price in railway innovation.

6. New Software and Platforms

6.1. Cloud2IR

KEYWORDS: Sensors - SHM (Structural Health Monitoring) - Sensors network - Open Geospatial Consortium - OGC

SCIENTIFIC DESCRIPTION

Cloud2IR is an helpful tool to build physicals models for the SHM of civil engineering structures.

In this context the software is deployed in the SenseCity-EQUIPEX driven by IFSTTAR (http://sense-city.ifsttar.fr/)

FUNCTIONAL DESCRIPTION

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.

- Partner: IFSTTAR
- Contact: Jean Dumoulin

This work has been developed during the ADT of Antoine Crinière, Cloud2SM.

6.2. PEGASE

KEYWORD: Sensors - SHM (Structural Health Monitoring)

SCIENTIFIC DESCRIPTION

PEGASE (Plate-forme Experte Générique pour Applications Sans-fil Embarquées) is a generic and high level wireless sensor platform. Currently, the setup of the new PEGASE 2 platform is finalized as the technological successor of the previous PEGASE platform developed by IFSTTAR. This PEGASE 1 platform is licensed and disseminated by the third party company A3IP since 2008 and has been sold in thousands of units.

Based on various feedback from monitoring applications of PEGASE, and due to the fast obsolescence of electronic devices, the design of the new PEGASE 2 platform has been launched in 2013. Some of the main functions of PEGASE are reinforced:

- Software genericity: use of a Linux embedded OS to make application development independent from the hardware, and to enable the user to manage the system without any 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) where each pluggable daughter board implements a specific function (sensing, 3G, Ethernet, communication, signal processing and relay control).
- Accurate time synchronization principle: based on an original GPS and PPS algorithm, PEGASE platform is one of the only boards able to time-stamp data from sensors or any event with high accuracy and in a deterministic way.

On PEGASE 2 platform, previous principles are maintained or extended. A full electronic design from scratch has been decided by the team in 2014 to maximize its capacities in terms efficiency, cost, energy consumption, etc. The main new characteristics of PEGASE 2 are:

- A “real” Linux kernel is now flashed inside the board based on a professional Debian 4.0 (or higher version) of Linux. This Linux branch is the only one validated by IEEE to suit embedded applications
- Previous SDK in C language has been ported and improved in C++ with a generalization of the signal/slot principle to offer end-users a full programing context based on “event driven developments”.
- Extended hardware capacities: GigaBytes of memory, multiple USB port, etc...
- PEGASE 2 board implements new hardware such as a on-board Battery Management System (BMS) to be able to manage an energy efficiency based on a battery and a solar cell; PEGASE 2 mother board integrates a MEMS Mpu9150 from Invenses company wich is a MEMS that provides Acceleration, Temperature and Gyroscope in 3D,...

In 2015 and 2016 various functional daughter boards have been designed to complete the PEGASE 2 panoply:

- 8 analog and 8 digital daughter boards
- LORA protocol Daughter Board
- 3G Daughter Board

Figure 6. PEGASE and PEGASE daughter board

In 2016, based on an industrial contract with the company SDEL-CC (subsidiary company of Vinci group) an important algorithm has been implemented in PEGASE 2 board to make it able to time stamp any physical event up to 10 nanoseconds (independently from the wireless protocol or the distances between the platform that could be some tens of kilometers). This time stamping ability is unique and makes PEGASE 2 the only wireless device in the world with such a time accuracy in a deterministic way and in universal time (based on its GSP/PPS principle).

The most significant development in the PEGASE 2 context is the development of a Generic Cloud Server Application:

- manage multiple instrumentation projects
- various sensors (based on PEGASE 1 or 2 or others) can be set up
- collect big data based on Mongo DB database
- visualize the graphs of data from sensors in f(t) on dynamic charts
- export data to files, through specific API, or to third-party software (Matlab, QT C++...)

In the last two years the Generic Supervisor became a professional software product that is transfered under industrial Licensing, e.g. to the companies Power Lan and Stimio. By the end of 2016, at least these 2 companies will be officially licensed by IFSTTAR to disseminate the Supervisor.

- 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

Figure 7. Supervisor

6.3. TrackingMecaSys

KEYWORDS: Bayesian estimation - Monte-Carlo - GPGPU - Kalman filter - Particular filter - Vibrating system

FUNCTIONAL DESCRIPTION

Implementation of a method based on the use of Bayesian modal parameter recursive estimation based on a particular Kalman filter algorithm with decoupled distributions for mass and stiffness. Algorithm optimized for a GPGPU implementation. This work has been done during ADT of Antoine Crinière and will be updated during the postdoc of S. Sen.

- Contact: Laurent Mevel

7. New Results

7.1. Outdoor InfraRed Thermography

7.1.1. Autonomous software architecture standardized for infrared and environmental SHM : Cloud2IR

Participants: Antoine Crinière, Jean Dumoulin, Laurent Mevel.

Cloud2IR is an autonomous software architecture, allowing multi-sensor connection (i.e. Infrared Thermography), dedicated to the long term monitoring of infrastructures. Past experimentations have shown the need as well as usefulness of such system. The system has been developed in order to cut down software integration time which facilitates the system adaptation to each experiment specificity. That is why we propose a bi-headed architecture. A specialized part, it represents the sensor specific development as well as their drivers and their different fixed configurations. In our case, as infrared camera are slightly different than other kind of sensors, the system implement in addition an RTSP server which can be used to set up the FOV as well as other measurement parameter considerations and a generic part, which can be seen as the data management side. This last part can be seen as the first embryo of a future generic framework dedicated to the data management of local multisensors (DaMaLoS). It is able to aggregate any sensor data, type or size and automatically encapsulate them in various generic data format as HDF5 or cloud data as OGC SWE standard. This whole part is also responsible of the acquisition scenario the local storage management and the network management through SFTP or SOAP for OGC Web services. Cloud2IR has been deployed on field since more than one year at the SenseCity outdoor test bed and several month at the Inria test bed, both located in France. The system aggregates various sensors as infrared camera, a GPS, multiple pyranometers, a weather station and a proprietary access to the SenseCity data viewer.[40][41]

7.1.2. GPU Improved quantitative analysis of Longterm Infrared-Thermography Data

Participants: Antoine Crinière, Jean Dumoulin, Laurent Mevel.

Since the past decade, infrared thermography coupled with inverse models based on 1d thermal quadrupoles have shown their usefulness in civil engineering by first showing their ability to assess the quantitative non destructive testing of concrete repaired by bonded CFRP plate over a wide area (i.e. repaired or reinforced concrete beams). On the other hand early implementations of long terms monitoring methods based on such approach have given their first results over a whole bridge deck. The experimental method, allow us to have the apparent surface temperature field evolution with time for a wide area divided in pixels. Knowing this specificity, the procedure aims to apply an independent model to each pixel in order to retrieve physical properties map. Such treatment can have a high computational cost. We propose various improvement of our procedure based on GPGPU paradigm in order to shorten the computational time. This study will detail an experimental procedure able to assess the long term thermal monitoring of a bridge deck over days and to draw properties maps of the inner structure. [28]

7.1.3. Infrared thermography for cultural heritage monitoring

Participant: Jean Dumoulin.

Radiation theory helps us to introduce infrared thermography. Infrared thermography is first presented in its passive mode and followed by considerations on active mode. Some processing analysis approaches are described. They belong to signal and image processing domain or to heat transfer domain. Illustration of results obtained with such analysis approaches are described on two experiments carried out in quasi laboratory conditions. Then, a case case study of the monitoring of the Viaduct Basento in Potenza (Southern Italy) is presented. Two features make fascinating this case study. The first one regards the fact that Viaduct Basento is probably the most important and visionary architectural work of the famous structural engineer Sergio Musmeci. The second aspect concerns the application, almost unique in the scientific literature, of an integrated diagnosis approaches combining a wide set of electromagnetic sensing technologies combined with advanced civil engineering analysis methodologies and tools.[44] [45] [22] [23]

7.2. Smarts roads and R5G

7.2.1. 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. [24]

7.3. Methods for building performance assessment

7.3.1. Building performance assessment

Participants: Jordan Brouns, Jean Dumoulin, Alexandre Nassiopoulos, Nicolas Le Touz.

Accurate building performance assessment is necessary for the design of efficient energy retrofit operations and to foster the development of energy performance contracts. An important barrier however is that simulation tools fail to accurately predict the actual energy consumption. Two methodology are adressed, first combining thermal sensor output and inverse algorithms to determine the key parameters of a multizone thermal model [15] then assessing wall thermal resistance estimation using infrared thermography and microwave coupling [38][34][43]

7.4. System identification

7.4.1. Variance estimation of modal parameters from subspace-based system identification

Participants: Michael Doehler, Laurent Mevel.

This work has been carried out in collaboration with Philippe Mellinger (former PhD student with Dassault Aviation, now CEA).

An important step in the operational modal analysis of a structure is to infer on its dynamic behavior through its modal parameters. When output-only data is available, i.e. measured responses of the structure, frequencies, damping ratios and mode shapes can be identified assuming that ambient sources like wind or traffic excite the system sufficiently. When also input data is available, i.e. signals used to excite the structure, input/output identification algorithms are used. The use of input information usually provides better modal estimates in a desired frequency range. When identifying the modal parameters from noisy measurement data, the information on their uncertainty is most relevant. In this work, new variance computation schemes for modal parameters are developed for four subspace algorithms, including output-only and input/output methods, as well as data-driven and covariance-driven methods. For the input/output methods, the known inputs are considered as realizations of a stochastic process. Based on Monte Carlo validations, the quality of identification, accuracy of variance estimations and sensor noise robustness are discussed. Finally these algorithms are applied on real measured data obtained during vibrations tests of an aircraft. [19] [37]

7.4.2. Bayesian parameter estimation for parameter varying systems using interacting Kalman filters

Participants: Antoine Crinière, Laurent Mevel, Jean Dumoulin.

Method based on the use of Bayesian modal parameter recursive estimation based on a particular Kalman filter algorithm with decoupled distributions for mass and stiffness. Particular Kalman filtering is a combination of two widely used Bayesian estimation methods working together: the particle filter (also called sequential Monte Carlo samplings) and the Kalman filter. Usual system identification techniques for civil and mechanical structures assume the availability of large set of data derived from a stationary quasi steady structure. On the opposite, several scenarios involve time varying structures. For example, due to interaction with aerodynamics in aeronautics, some critical parameter may have to be monitored, for instability monitoring (leading possibly to flutter) of in flight data due to fuel consumption and speed change. This relates to the monitoring of time varying structural parameters such as frequencies and damping ratios. The main idea of a particular Kalman filter is to consider stochastic particles evolving in the parameter space. For each particle, a corresponding linear state is recursively estimated by applying a Kalman filter to the mechanical system, whose modal parameters are driven by the evolution of this time-varying particle. In order to provide fast and convincing results for large time varying structure, such as an airplane, the execution time of the method has to be improved. Within the Cloud2sm ADT a GPGPU implementation of the algorithm have been developed, now a post-doctoral position have been obtained to improve the algorithm reliability.[29]

7.4.3. Stability of the Kalman filter for continuous time output error systems

Participant: Qinghua Zhang.

This work has been carried out in collaboration with Boyi Ni (SAP Labs China).

The stability of the Kalman filter is usually ensured by the uniform complete controllability *regarding the process noise* and the uniform complete observability of linear time varying systems. This work studies the case of continuous time *output error* systems, in which the process noise is totally absent. The classical stability analysis assuming the controllability regarding the process noise is thus not applicable. It is shown in this work that the uniform complete observability *alone* is sufficient to ensure the asymptotic stability of the Kalman filter applied to time varying *output error* systems, regardless of the stability of the considered systems themselves. The exponential or polynomial convergence of the Kalman filter is then further analyzed for particular cases of stable or unstable output error systems. The results of this work have been published in [20].

7.4.4. Parameter uncertainties quantification for finite element based subspace fitting approaches

Participants: Guillaume Gautier, Laurent Mevel, Michael Doehler.

This work has been carried out in collaboration with Jean-Mathieu Mencik and Roger Serra (INSA Centre Val de Loire).

We address the issue of quantifying uncertainty bounds when updating the finite element model of a mechanical structure from measurement data. The problem arises as to assess the validity of the parameters identification and the accuracy of the results obtained. A covariance estimation procedure is proposed about the updated parameters of a finite element model, which propagates the data-related covariance to the parameters by considering a first-order sensitivity analysis. In particular, this propagation is performed through each iteration step of the updating minimization problem, by taking into account the covariance between the updated parameters and the data-related quantities. Numerical simulations on a beam show the feasibility and the effectiveness of the method. [31]

7.4.5. Embedded subspace-based modal analysis and uncertainty quantification

Participants: Vincent Le Cam, Michael Doehler, Mathieu Le Pen, Ivan Guéguen, Laurent Mevel.

Operational modal analysis is an important step in many methods for vibration-based structural health monitoring. These methods provide the modal parameters (frequencies, damping ratios and mode shapes) of the structure and can be used for monitoring over time. For a continuous monitoring the excitation of a structure is usually ambient, thus unknown and assumed to be noise. Hence, all estimates from the vibration measurements are realizations of random variables with inherent uncertainty due to unknown excitation, measurement noise and finite data length. Estimating the standard deviation of the modal parameters on the same dataset offers significant information on the accuracy and reliability of the modal parameter estimates. However, computational and memory usage of such algorithms are heavy even on standard PC systems in Matlab, where reasonable computational power is provided. In this work, we examine an implementation of the covariance-driven stochastic subspace identification on the wireless sensor platform PEGASE, where computational power and memory are limited. Special care is taken for computational efficiency and low memory usage for an on-board implementation, where all numerical operations are optimized. The approach is validated from an engineering point of view in all its steps, using simulations and field data from a highway road sign structure. [33]

7.5. Damage diagnosis

7.5.1. Estimation of distributed and lumped ohmic losses in electrical cables

Participants: Nassif Berrabah, Qinghua Zhang.

This work has been carried out in the framework of a CIFRE PhD project in collaboration with EDF R&D.

Cables play an important role in modern engineering systems, from power transmission to data communication. In order to ensure reliable and cost-efficient operations, as well as a high level of performance, efficient tools are needed to assess and monitor cables. Hard faults are well handled by existing techniques, whereas soft fault diagnosis still represents an important challenge for current researches. This work focuses on the detection, localization, and estimation of resistive soft fault in electrical cables from reflectometry measurements. A method for the computation of the distributed resistance profile along the cable under test has been developed. Both experimental and simulation results confirm its effectiveness, as reported in the conference paper [26]. A patent based on this work has been registered at INPI (see Section 10.1.4.1).

7.5.2. Fault detection, isolation and quantification from Gaussian residuals

Participants: Michael Doehler, Laurent Mevel, Qinghua Zhang.

Despite the general acknowledgment in the Fault Detection and Isolation (FDI) literature that FDI are typically accomplished in two steps, namely residual generation and residual evaluation, the second step is by far less studied than the first one. This work investigates the residual evaluation method based on the local approach to change detection and on statistical tests. The local approach has the remarkable ability of transforming quite general residuals with unknown or non Gaussian probability distributions into a standard Gaussian framework, thanks to a central limit theorem. In this work, the ability of the local approach for fault quantification is exhibited, whereas previously it was only presented for fault detection and isolation. The numerical computation of statistical tests in the Gaussian framework is also revisited to improve numerical efficiency. An example of vibration-based structural damage diagnosis is presented to motivate the study and to illustrate the performance of the proposed method. [17]

7.5.3. *Performance of damage detection in dependence of sample length and measurement noise*

Participants: Saeid Allahdadian, Michael Doehler, Laurent Mevel.

In this work the effects of measuring noise and number of samples is studied on the stochastic subspace damage detection (SSDD) technique. In previous studies, the effect of these practical parameters was examined on simulated measurements from a model of a real structure. In this study, these effects are formulated for the expected damage index evaluated from a Chi-square distributed value. Several theorems that describe the effects are proposed and proved. These theorems are used to develop a guideline to serve the user of the SSDD method to face these effects. [25]

7.5.4. *Statistical damage localization with stochastic load vectors*

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

The Stochastic Dynamic Damage Locating Vector (SDDLV) method is an output-only damage localization method based on both a Finite Element (FE) model of the structure and modal parameters estimated from output-only measurements in the damage and reference states of the system. A vector is obtained in the null space of the changes in the transfer matrix computed in both states and then applied as a load vector to the model. The damage location is related to this stress where it is close to zero. In previous works an important theoretical limitation was that the number of modes used in the computation of the transfer function could not be higher than the number of sensors located on the structure. It would be nonetheless desirable not to discard information from the identification procedure. In this work, the SDDLV method has been extended with a joint statistical approach for multiple mode sets, overcoming this restriction on the number of modes. The new approach is validated in a numerical application, where the outcomes for multiple mode sets are compared with a single mode set. From these results, it can be seen that the success rate of finding the correct damage localization is increased when using multiple mode sets instead of a single mode set. [27]

7.5.5. *Classification of vibration-based damage localization methods*

Participant: Michael Doehler.

This work, issued from the COST Action TU1402, is in collaboration with M.P. Limongelli (Politecnico Milan), E. Chatzi (ETH Zürich), G. Lombaert and E. Reynders (both KU Leuven).

After a brief review of vibration based damage identification methods, three different algorithms for damage identification are applied to the case of the benchmark Z24 bridge. Data-driven as well as model-based methods are discussed, including input-output algorithms for taking into account the effect of environmental and/or operational sources on the variability of damage features. A further class of data-driven methods that use finite element information is finally introduced as a possible future development. [35]

7.5.6. *Structural system reliability updating with subspace-based damage detection information*

Participant: Michael Doehler.

This work is in collaboration with S. Thöns (DTU).

Damage detection systems and algorithms (DDS and DDA) provide information of the structural system integrity in contrast to e.g. local information by inspections or non-destructive testing techniques. However, the potential of utilizing DDS information for the structural integrity assessment and prognosis is hardly exploited nor treated in scientific literature up to now. In order to utilize the information provided by DDS for the structural performance, usually high computational efforts for the pre-determination of DDS reliability are required. In this work, an approach for the DDS performance modelling is introduced building upon the non-destructive testing reliability which applies to structural systems and DDS containing a strategy to overcome the high computational efforts for the pre-determination of the DDS reliability. This approach takes basis in the subspace-based damage detection method and builds upon mathematical properties of the damage detection algorithm. Computational efficiency is gained by calculating the probability of damage indication directly without necessitating a pre-determination for all damage states. The developed approach is applied to a static, dynamic, deterioration and reliability structural system model, demonstrating the potentials for utilizing DDS for risk reduction. [30]

7.5.7. Structural system model updating based on different sensor types

Participants: Dominique Siegert, Xavier Chapeleau, Ivan Guéguen.

Detecting and quantifying early structural damages using deterministic and probabilistic model updating techniques can be achieved by local information in a form of optical strain measurement. The strategy consists in updating physical parameters associated to damages, such as Young's modulus, in order to minimize the gap between the numerical strain obtained from finite element solves and the strain sensor outputs. Generally, the damage estimation is an ill-posed inverse problem, and hence requires regularization. Herein, three model updating techniques are considered involving different type of regularization: classical Tikhonov regularization, constitutive relation error based updating method and Bayesian approach [21]. This work follows an experimental campaign carried out on a post tensioned concrete beam with the aim of investigating the possibility to detect early warning signs of deterioration based on static and/or dynamic tests. Responses of a beam were measured by an extensive set of instruments consisting of accelerometers, inclinometers, displacement transducers, strain gauges and optical fibers. [18].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. PhD project with EDF – Electrical device ageing monitoring

Participants: Nassif Berrabah, Qinghua Zhang.

A joint PhD project between Inria and EDF (ElectricitÈ 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 ageing 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.

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.

In 2016, uncertainty quantification for modal analysis has been launched http://www.svibs.com/newsletter/newsletter_2016_09.aspx.

8.1.3. Contracts with A3IP

Participant: Vincent Le Cam.

Since 2008, IFSTTAR has licensed the company A3IP to sell licenses of the PEGASE 1 platform (previous version of PEGASE 2 as mentioned above). A3IP sells them to to companies, laboratories or any third-party partner interested in in-situ monitoring (SHM) with smart and wireless sensors. Since 2008, about 1000 of PEGASE 1 units have been sold, plus hundreds of the following items:

- daughter boards: 3G / Ethernet communications, Analog to Digital data acquisition...
- sensors: accelerometer, strain gauges, temperature...
- specific packaging to make the PEGASE 1 solution ready to use in waterproof conditioning

For example, in 2016, A3IP has provided a complete panoply of PEGASE-1 Vibration Monitoring system with more than 30 PEGASE1 units to ensure the monitoring of the new High Speed Train line in west of France (Bretagne Pays de la Loire high speed railway).

This non exclusive license is clearly a success in terms of dissemination.

8.1.4. Contract with SNCF: DEMETER

Participant: Vincent Le Cam.

DEMETER is one of the major projects for I4S in terms of strategy, scientific and technological impact.

DEMETER is a meta project whose global objective is the validation of the contribution of the Internet of Things (IOT) applied to the Health Monitoring of Railways Items. SNCF and IFSTTAR have signed a roadmap for safety relevant items, where wireless monitoring and smart algorithms could bring strong improvements to SNCF in terms of real-time maintenance or predictive maintenance. Those items are, amongst others:

- Crossing engine motor monitoring
- Needle motor monitoring
- Axel counter monitoring
- Train detection pedal monitoring

In each case, a prototype of a specific PEGASE 2 sensor is designed, installed along in-situ railways lines under exploitation and data are transmitted wireless to the cloud supervisor at IFSTTAR for evaluation in SHM algorithms. IFSTTAR's engineers Arthur Bouche, Laurent Lemarchand and David Pallier are contributing to this project.

In particular, SNCF and IFSTTAR are able to perform the entire validation process quickly in few months: from the algorithm to the electronic design and installation. In 2016, the consortium reached 2 milestones: the PEDAL-LORA monitoring sensor has been awarded the European Railway Cluster Price in railway innovation; this system is now becoming an industrial product, directly designed by a third-party company for SNCF. In 2017, the roadmap will be extended with a specific focus on SHM algorithms implementation to help SNCF moving from big data to smart data.

8.1.5. Contracts with SDEL-CC (VINCI Group)

Participant: Vincent Le Cam.

In 2016, a contract has been signed with the company SDEL-CC, 100% daughter of the VINCI Group, Energy department. The project exploits the unique time stamp capacity of PEGASE 2 up to 50 nanosecond, independently of distances in the network of PEGASE2 nodes. The synchronization capacity is employed to design a sensor prototype based on PEGASE2 to time-stamp the current wave after a lightning impact on a high-voltage line. By knowing the exact time, the wave can be seen at each extremity of the electrical line to localize accurately the lightning impact point. IFSTTAR's engineers Arthur Bouche and Laurent Lemarchand have contributed to this project.

During 2016, we have improved its embedded algorithms on PEGASE 2 platform to:

- take into account some specific GPS frames that output from its GPS receiver and give practical information on time drift
- take into account the temperature effect
- auto compute the real quartz period on each specific PEGASE 2 board

Two PEGASE 2 platforms are now able to time stamp an event with an accuracy of less that 10 nanoseconds. This leads to a precision of around 3 m for Lightning localization.

In 2017 in situ validation will be achieved on a real operated electric line.

8.1.6. Collaboration with SIEMENS : CityVal Rennes

Participant: Jean Dumoulin.

A first Winter season measurements campaign on the 100m metro structure mock-up built at IFSTTAR test track facilities in Nantes was carried out in 2016. It was completed by in situ instrumentation including coupling of infrared thermography with other measurements techniques for long term monitoring during several months. A new campaign is under preparation and will be launched in 2017. This collaboration is also connected with the new automated metro line B under construction in Rennes.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. MONEOL - project with CEAtech Pays de Loire

Participants: Ivan Guéguen, Guillaume Gautier, Laurent Mevel.

Type: CEAtech PDL

Objectif: Modal analysis of wind turbines using new sensors

Duration: 11/2015 to 11/2017.

Coordinator: Louis Marie Cotineau (IFSTTAR)

Inria contact: Guillaume Gautier

Abstract: The MONEOL project aims to demonstrate the feasibility of using Morphosense as a vibration monitoring system for wind turbines. It is proposed to set up a demonstrator consisting of a monitoring system placed in the mast of the wind turbine, a vibration analysis system and a visualization of the vibratory state at the CEA-Tech premises, located on the Technocampus Ocean of Nantes allowing to visualize in real time (quasi) the modal deformations of the mast of the wind turbine. This system consists of the following elements:

The demonstrator consists of the monitoring system placed in the wind turbine of a video screen displaying in real time indicators to evaluate the state of health of the structure:

- Modal parameters (eigen frequencies, modal damping, modal deformations) over time and associated uncertainties.
- Indicators of detection and localization of damage.

The demonstrator will also be able to display a video of the wind turbine in operation. In order to validate the Morphosense sensor, a reference system is added to it, consisting of conventional accelerometer sensors.

9.1.2. *Interactive Communication (InterCom): Massive random access to subsets of compressed correlated data*

Participants: Jean Dumoulin, Antoine Crinière.

Type: Labex COMINLABS

Objectif: Massive random access to large-scale sensor network (Smart Cities)

Duration: Since November 2016 to Nov. 2019.

Coordinator :Aline Roumy, Thomas Maugey (Sirocco), Jean Dumoulin (I4S)

Partners: Elsa Dupraz (Lab-STICC), Aline Roumy (IRISA, Sirocco team), Michel Kieffer (L2S), Thomas Maugey(IRISA, Sirocco team), CentraleSupelec, Univ. Paris Sud.

Inria contact: Jean Dumoulin

Abstract: This project aims to develop novel compression techniques allowing massive random access to large databases. Indeed, we consider a database that is so large that, to be stored on a single server, the data have to be compressed efficiently, meaning that the redundancy/correlation between the data have to be exploited. The dataset is then stored on a server and made available to users that may want to access only a subset of the data. Such a request for a subset of the data is indeed random, since the choice of the subset is user-dependent. Finally, massive requests are made, meaning that, upon request, the server can only perform low complexity operations (such as bit extraction but no decompression/compression).

Algorithms for two emerging applications of this problem will be developed: Free-viewpoint Television (FTV) and massive requests to a database collecting data from a large-scale sensor network (such as Smart Cities) in which I4S is involved.

9.1.3. *MAG2C-Pont Tabarly*

Participants: Ivan Guéguen, Jean Dumoulin.

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.

Based on accelerometer measurements, the vibration behaviour will be monitored and structural defects detected. Coupled with a wireless data transmission system type or wifi 3g, remote monitoring is envisaged. The different objectives are

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

An accelerometer-based distributed network on the structure is installed and connected to a data acquisition system and a modem 3g for continuous remote measurements, which will be available on the internet.

9.1.4. MAG2C-MOSIWIND (MOnitoring of Structural Integrity of an onshore WIND turbine's slab foundation and tower)

Participants: Xavier Chapeleau, Ivan Guéguen.

Type: GIS

Objectif: MOnitoring of Structural Integrity of an onshore WIND turbine's slab foundation and tower

Duration: Since 2015

Coordinator : LIRGEC

Partners: IFSTTAR, CSTB, Nantes Métropole, Université de Nantes, ECN, Valorem, Valréa and Valémo

Inria contact: Xavier Chapeleau

Abstract: The project deals with the instrumentation of an onshore WIND turbine's slab foundation and tower. The aim is to experiment sensors and methods for structural integrity monitoring of an onshore wind turbine under real conditions and to qualify them over long term. Before casting, the concrete slab foundation (20m in diameter, 3.85m high, 450m3 of concrete, 48T of reinforcement) was first instrumented with continuous optical fibers, optical strain gauges, temperature sensors and accelerometers. Afterwards, accelerometers were placed in the mast. Data obtained by these different sensors will help, on the one hand, to monitor changes in the dynamic behavior of the structure in order to verify that they remain within the limits fixed during the design and, on the other hand, to detect any damage that could be critical for the safety of the structure. For this, SSI methods under ambient vibration will be applied.

9.1.5. 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

Objective: rail track SHM

Duration: 11/2014 to 11/2018

Coordinator: RAILENIUM

Partners: IFSTTAR, EIFFAGE, RFF, LGCgE

Inria contact: Ivan Guéguen

Abstract: This project aims at instrumenting 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 for environmental conditions (temperature, precipitation on the site).
- Accelerometers, to monitor the dynamic behavior of the track, with measurements at several levels: the hammer beams on top of the grave-bitumen layer, on top of the soil.
- Instrumentation of severe bitumen strain gauges for measuring the longitudinal and transverse tensile strains, 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.

9.2.2. ANR Resbati

Participant: Jean Dumoulin.

Type: ANR

Objectif: In-situ measurements of thermal wall resistance

Duration: 10/2016 to 10/2019

Coordinator: Laurent ibos

Partners : IFSTTAR, CERTES, CEREMA, CSTB, LNE, THEMACS, AFNOR

Inria contact: Jean Dumoulin

Abstract: Thermal insulation of opaque walls remains an essential point for improving the energy efficiency in buildings. Indeed, the number of badly insulated buildings in France is still very important. In addition, current thermal regulations set high requirements in terms of thermal insulation and will continue to be more rigorous as new building will be energy-positive with the French RT2020. However, there is no systematic method for measuring the thermal insulation level of the building walls. Their thermal performance must be controlled for renovation of the building, during its construction, for its delivery or during use. The need of a method of in-situ control of walls is more relevant than ever. Such a measurement at the wall level is an interesting complement to global methods (co-heating, etc.) that concern the whole building energy balance. The physical parameter representing the quality of the wall thermal insulation is its thermal resistance. Currently, methods for measuring this parameter exist, either in the form of laboratory or exploratory methods, or in the form of international standards or draft standards. However, each of these methods does not meet all the conditions guaranteeing a general measurement: use on any type of wall and at any time of the year, low measurement duration, ease of use, moderate cost. The RESBATI project (in-situ measurement of the thermal resistance of building walls) aims at developing an in-situ measurement device that respects these specifications. The measuring means is infrared thermography in active approach. The uncertainty and the limitations of the measurement will be identified during the project. Infrared thermography in passive mode has demonstrated for many years its ability to reveal the presence of insulation defects in buildings. However, it is essentially a qualitative tool. The active approach of infrared thermography is not very used for building investigation and is a promising way for obtaining quantitative information such as the thermal resistance of the wall to investigate. Indeed research results have already shown that this approach could be used to obtain quantitative estimations of the thermal resistance of opaque building walls. The RESBATI project will demonstrate the potential of the active approach so that control can be performed in any season, for any type of building and any use (occupied or not) and quickly. The passive approach might nevertheless be used as a complement because it does not require the use of additional equipment ensuring the thermal load of the wall to diagnose and provides access to larger wall surfaces to analyze. The consortium brings complementary partners together working at different levels of the building: research laboratories, technical center, national metrology laboratory, company and standards organization. The advanced knowledge and past achievements of the various partners on the subject make it possible to develop such a method with measurement uncertainty and the associated prototypes. Many facilities will be available for qualification of prototypes: climate rooms for laboratory testing, existing buildings for in-situ qualifications. Thus, a wide variety of walls (structure and isolation level) can be tested. Moreover, these buildings have different uses (residential or service buildings). In conclusion of the project, measurements will be carried out by future end-users of the device.

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. (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.

9.3.1.2. INFRASTAR (Innovation and Networking for Fatigue and Reliability Analysis of Structures – Training for Assessment of Risk)

Participant: Xavier Chapeleau.

Call: H2020-MSCA-ITN-2015 (Horizon 2020 – Marie-Sklodowska Curie Actions – Innovative Training Networks)

Type of Action: MSCA-ITN-ETN

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

Duration: 48 months since 2016 May 1st

Coordinator: Odile Abraham (IFSTTAR)

Academic and industrial Partners: IFSTTAR, UNIVERSITY OF AALBORG, BAM, EPFL, GuD Consult Gmbh, COWI A/S, NeoStrain, PHIMECA

Inria contact: X. Chapeleau

Website: http://infrastar.eu/

Abstract: The aim of INFRASTAR project is to develop tools combining modeling and measurements for the prediction of the fatigue behavior of concrete structures (bridges and foundations of wind turbines) with the ultimate objective of establishing an efficient strategy for inspection and reinforcement operations. In the second half of 2016, 12 young researchers were recruited to carry out and cross-examine research on monitoring and auscultation (WP 1), structural models (WP 2) and reliability of approaches for decision-making (WP 3). In this project, a phd student (Antoine Bassil) was recruited (Nov. 2016) on the fatigue monitoring of concrete structure by fibre-optic sensors.

9.3.2. Collaborations in European Programs, Except FP7 & H2020

9.3.2.1. 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.

9.3.2.2. 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 strategies and structural performance” and member of the steering committee.

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.

9.3.3. Other European Programs

9.3.3.1. Innobooster

Participants: Michael Doehler, Laurent Mevel.

Together with SVS, we got the Danish Innobooster innovation grant “Robust Operational Modal Analysis using Modal Uncertainty Quantification” 2015-2016, for industrial research and transfer. The result of the development in this project is the transfer of our uncertainty quantification algorithm [19] to SVS' ARTeMIS software http://www.svibs.com/newsletter/newsletter_2016_09.aspx.

9.4. International Initiatives

9.4.1. Informal International Partners

9.4.1.1. Collaboration with CNR, Italy

Participants: Jean Dumoulin, Nicolas Le Touz.

Non destructive testing on outdoor structures by coupling infrared thermography with ground penetrating radar is one of the topic addressed in this collaboration. A new one about TerHertz is starting.

9.4.1.2. 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 2015 for 3 years.

9.4.1.3. Collaboration with BAM, Germany

Participants: Laurent Mevel, Michael Doehler, Eva Viefhues.

Eva Viefhues is currently PhD student of Laurent Mevel and Michel Doehler in Berlin, financed by BAM. M. Doehler is also associate researcher of the BAM institut since 2016.

9.4.1.4. Collaboration with Politecnico di Milano, Italy

Participants: Michael Doehler, Dominique Siegert, Ivan Guéguen, Xavier Chapeleau.

During COST Action TU 1402 and M.P. Limongelli's research stay at IFSTTAR, collaboration with Politecnico di Milano has started, resulting in several joint publications in 2016 [35], [18], [21]. A joint Master student project is in progress, and a french-italian PhD project is planned.

9.4.2. Participation in Other International Programs

The team has been awarded a MITACS grant. It allowed us to host S. Allahdadian for 3 months in 2016.

9.5. International Research Visitors

9.5.1. Visits of International Scientists

S. Allahdadian from British Columbia University has visited us for 3 months in 2016 thanks to a MITACS grant.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Selection

10.1.1.1. Member of the Conference Program Committees

J.Dumoulin is

- member of the scientific committee of the GI Division (Geosciences Instrumentation and Data Systems) of EGU (European Geosciences Union) for infrastructure instrumentation and monitoring since April 2013. (http://www.egu.eu/gi/structure/)
- member of the scientific committee of QIRT (quantitative Infrared Thermography) since February 2014 (http://www.qirt.org/)
- organizer and chair of a session at EGU 2016 (http://www.egu2016.eu/).

L. Mevel

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

V. Le Cam is head and general secretary of the EWSHM scientific committee.

Q. Zhang:

- Member of IFAC Technical Committee on Modelling, Identification and Signal Processing.
- Member of IFAC Technical Committee on Fault Detection, Supervision and Safety of Technical Processes.

M. Doehler

- was organizer of an invited session at EWSHM 2016.
- session organizer at two COST workshops (http://www.cost-tu1402.eu/events).

10.1.1.2. Reviewer

V. Le Cam was session chairman for the EWSHM 2016 in Bilbao

L. Mevel was reviewer and session chairman for the EWSHM 2016 in Bilbao, and reviewer for IFAC WC 2017

Q. Zhang was reviewer for CDC 2016, IFAC WC 2017

M. Doehler was reviewer and session chairman for EWSHM 2016 in Bilbao, and reviewer for MED 2016, IFAC WC 2017

J. Dumoulin was reviewer and session chairman for QIRT 2016 and at EGU 2016 in GI division

10.1.2. Journal

10.1.2.1. member of the Editorial Boards

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 of Intelligent Industrial Systems.

J. Dumoulin is member of the editorial board of the journal of Quantitative Infrared Thermography.

J. Dumoulin is member of the editorial board of the journal of Geoscientific Instrumentation and Data Systems.

10.1.2.2. Reviewer - Reviewing activities

X. Chapeleau was reviewer for Journal: Sensors and Journal of Civil Structural Health Monitoring

L. Mevel was reviewer for Mechanical Systems and Signal Processing, journal of Sound And Vibration and Journal of Control and SHM.

M. Doehler was reviewer for Automatica, International Journal of Control, International Journal of Systems Science, Mechanical Systems and Signal Processing, Journal of Sound and Vibration, Mathematical Problems in Engineering, Smart Materials and Structures, Journal of Intelligent Material Systems and Structures

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

10.1.3. Invited Talks

J. Dumoulin was invited speaker at the 4th Youth in Conservation of Cultural heritage YOCOCU 2016, 21-23 September 2016, Madrid, Spain.

J. Dumoulin was invited keynote speaker at ERICE in October 2016.

J. Dumoulin was invited speaker at SFT 2016 in March 2016.

M. Mogoro (from SNCF) and V. Le Cam have been invited to give a keynote at the first SHM Conference dedicated to Railway in Qingdao, China, on October 2016 http://www.crrcgc.cc/iwshm-rs/english/.

V. Le Cam have was invited speaker at the "NDT Conference organized by Airbus Group at Pondichery, India, January 2016"

10.1.4. Scientific Expertise

10.1.4.1. Method and device for localizing faults in an electrical cable

Participants: Nassif Berrabah, Qinghua Zhang.

In modern engineering systems, fault diagnosis is frequently an integrated functionality for various components, but rarely for electrical cables. The fast development of electronic devices is accompanied by more and more connecting cables. The reliability of electrical connections becomes a crucial issue because of their large number. Moreover, some cables are operated under severe conditions, such as extreme temperature, nuclear radiation, humidity, mechanical strain, etc.. Based on the work reported in Section 7.5.1, a patent has been registered at INPI jointly by EDF and Inria [46]. It is about a method for detecting, localizing and quantifying resistive faults in a cable, by means of estimating the series resistance per unit length distributed along the cable from reflectometry measurements made at the ends of the cable. Its fast numerical computation makes it suitable for real time applications.

10.1.4.2. Scientific Expertise in European Calls

Participant: Vincent Le Cam.

V. Le Cam : Expertise of a specific EUROPEAN SME project in the call EUROSTARS.

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

Licence Professionnelle TAM : J. Dumoulin, thermographie infrarouge active, 16h, 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 2 ITII, J. Dumoulin, , BTP, module Maintenance et réhabilitation des ouvrages, « Transferts thermiques dans les Structures : Des principes physiques à l'application sur site réel », 12 h, Ecole Centrale de Nantes(ECN).

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, 16h, TP, embedded systems under Linux Operating System, France

Polytech, V. Le Cam, 14h, TP, embedded systems under Linux Operating System, France

Master 1 informatique, M. Doehler, 24 TD projet recherche, Université de Rennes 1 & ENS Rennes, France

Licence Pro Mesures physiques, X. Chapeleau, Mesures optiques, 15h, IUT de St Nazaire, Université de Nantes, France

10.2.2. Supervision

PhD : Antoine Bassil, *Fibre-optic sensor for fatigue monitoring*, D. Leduc, O. Abraham and X. Chapeleau, Ecole doctorale SPIGA, Université de Nantes, since November 2016.

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

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

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

PhD : Nicolas Le Touz. *Design and study of positive energy transport infrastructures: from thermomechanical modeling to the optimization of such energy systems* J. Dumoulin. at Ecole Centrale Nantes (ECN) since 2015.

PhD : Thibault Toullier. *Simultaneous characterization of the radiative properties and temperatures of envelopes of structures in natural environment by multispectral infrared thermography* L. Mevel, J. Dumoulin and M. Doehler. Ecole doctorale MATISSE, Université de Rennes 1, since November 2016.

PhD : Saeid Allahdadian, *Methods for vibration-based damage assessment*, M. Doehler, University of British Columbia, Canada, since 2015.

PhD : Eva Viefhues, *Statistical damage localization for civil structures*, L. Mevel and M. Doehler, Ecole doctorale MATISSE, Université de Rennes 1, since November 2016.

J. Dumoulin is associate professor at Laval University, Canada.

M. Doehler is associate researcher at BAM, Germany.

10.3. Popularization

J. Dumoulin was in charge of hybrid/solar road that was demonstrated at COP21 and COP22.

11. Bibliography

Major publications by the team in recent years

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