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Activity Report 2017

Project-Team I4S

Statistical Inference for Structural Health Monitoring

RESEARCH CENTER
Rennes - Bretagne-Atlantique

THEME
Optimization and control of dynamic systems

Table of contents

Project-Team I4S

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

Keywords:

Computer Science and Digital Science:

A6.1.5. - Multiphysics modeling
A6.2.1. - Numerical analysis of PDE and ODE
A6.2.4. - Statistical methods
A6.2.5. - Numerical Linear Algebra
A6.2.6. - Optimization
A6.3.1. - Inverse problems
A6.3.3. - Data processing
A6.3.4. - Model reduction
A6.3.5. - Uncertainty Quantification
A6.4.3. - Observability and Controlability

Other Research Topics and Application Domains:

B3.1. - Sustainable development
B3.2. - Climate and meteorology
B3.3.1. - Earth and subsoil
B4.3.2. - Hydro-energy
B4.3.3. - Wind energy
B4.3.4. - Solar Energy
B5.1. - Factory of the future
B5.2. - Design and manufacturing
B5.9. - Industrial maintenance
B6.5. - Information systems
B7.2.2. - Smart road
B8.1. - Smart building/home
B8.1.1. - Energy for smart buildings
B8.1.2. - Sensor networks for smart buildings
B8.2. - Connected city

1. Personnel

Research Scientists

Laurent Mevel [Team leader, Inria, Senior Researcher, HDR]
Jean Dumoulin [IFSTTAR, Researcher, scientific co-head of I4S]
Qinghua Zhang [Inria, Senior Researcher, HDR]
Xavier Chapeleau [IFSTTAR, Researcher]
Michael Doehler [Inria, Researcher]

Faculty Member

Frederic Gillot [Ecole centrale de Lyon, Associate Professor, since September 2017]

Post-Doctoral Fellows

Guillaume Gautier [Inria since September 2017, CEA-tech until August 2017]
Ludovic Gaverina [IFSTTAR]
Subhamoy Sen [Inria, until May 2017]

PhD Students

Saeid Allahdadian [UBC Vancouver, until June 2017]
Nassif Berrabah [EDF, until November 2017]
Md Delwar Hossain Bhuyan [Inria, until November 2017]
Nicolas Le Touz [IFSTTAR]
David Pallier [IFSTTAR, since November 2017]
Antoine Bassil [IFSTTAR]
Thibaud Toullier [Inria]
Eva Viefhues [BAM]
Francesco Giordano [Politecnico di Milano, since November 2017]

Technical staff

Antoine Crinière [Inria]
Quentin Bossard [IFSTTAR]
Ivan Guéguen [IFSTTAR]
Vincent Le Cam [IFSTTAR, Researcher, Team leader of SII Lab at IFSTTAR]
Mathieu Le Pen [IFSTTAR]

Administrative Assistants

Helene de La Ruée [Inria]
Yveline Gourbil [IFSTTAR]

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 challenge for I4S's SHM projects 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 of Y_n whose length 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 should not perturb the detection. Of course, from a structural health monitoring point of view the knowledge of the true load is 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 being 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 constitue 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 :

$$\theta \triangleq \left(\begin{array}{c} \Lambda \\ \mathrm{vec}\Phi \end{array} \right) \tag{6}$$

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 [62].

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

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

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 :

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

where:

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

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:

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

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

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

3.1.2.1. *Residual associated with subspace identification.*

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

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

and to define the residual vector:

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

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 [56] that the residual is asymptotically Gaussian :

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

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

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

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 [55].

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

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

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

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

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

3.2. Thermal methods

3.2.1. Infrared 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.

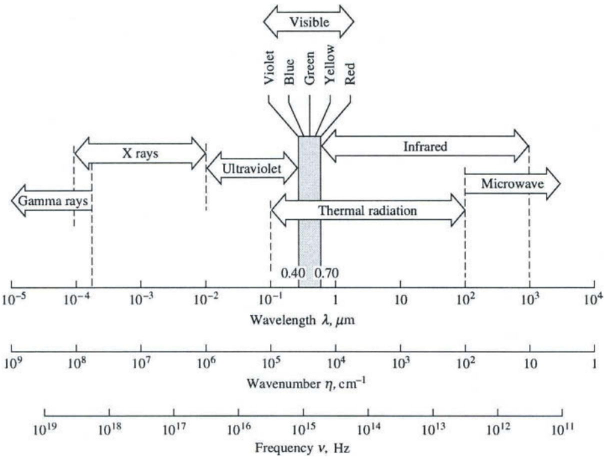

Figure 1. Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

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

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

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 in 1901, allows 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.

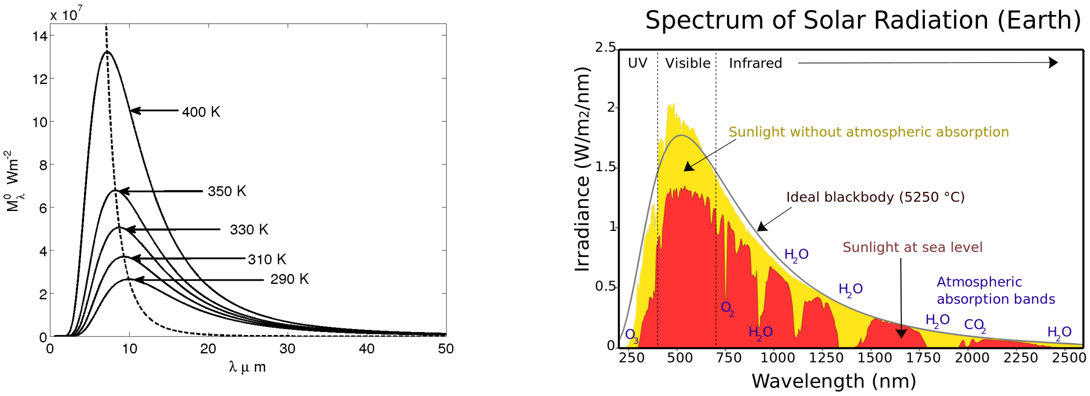

Figure 2. Left: Plank's law at various temperatures - Right: Energy spectrum of the atmosphere

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.

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

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

$$\nabla\mathcal{F}(P) = 2\left[-\frac{\partial AP^T}{\partial P}\right][AP - \mathcal{M}] = 2J(P)^T [AP - \mathcal{M}] \tag{29}$$

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 (30).

$$P^{k+1} = P^k + \left[\left(J^k\right)^T J^k + \mu^k \Omega^k \right]^{-1} \left(J^k\right)^T \left[\mathcal{M} - A(P^k) \right] \tag{30}$$

Equation (30) 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 of connection 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. 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], [61]. 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 [63], [59]. The main results concern, on the one hand, simple star-shaped networks from measurements made at a single node, on the other hand, complex networks of arbitrary topological structure with complete node observations.

Though initially our studies on reflectometry were aiming at applications in electrical engineering, since the creation of the I4S team, 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 [60]

$$\begin{aligned} &\frac{\partial}{\partial z} V(t,z) + L(z) \frac{\partial}{\partial t} I(t,z) + R(z) I(t,z) = 0 \\ &\frac{\partial}{\partial z} I(t,z) + C(z) \frac{\partial}{\partial t} V(t,z) + G(z) V(t,z) = 0 \end{aligned} \tag{31}$$

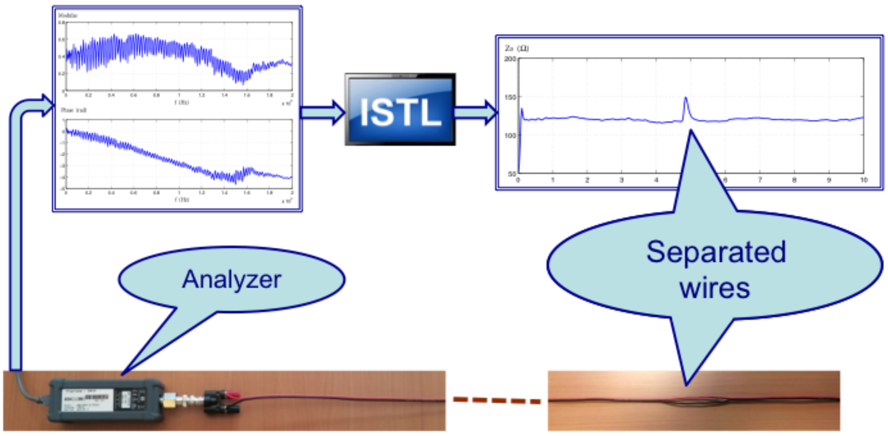

Figure 3. Inverse scattering software (ISTL) for cable soft fault diagnosis.

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

$$V(t,a) = V_s(t) - R_s I(t,a). \tag{32}$$

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

$$V(t,b) \quad = R_L I(t,b). \tag{33}$$

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.

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, 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 [58]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [57]. After having completed some theoretic results directly linked to practice [14], [61], 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 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 obtain a frequency domain model, 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

$$\begin{aligned} \nu_1(\omega, x) &= \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega, x) - Z_0^{\frac{1}{2}}(x)I(\omega, x)\right] \\ \nu_2(\omega, x) &= \frac{1}{2}\left[Z_0^{-\frac{1}{2}}(x)U(\omega, x) + Z_0^{\frac{1}{2}}(x)I(\omega, x)\right] \end{aligned} \tag{34}$$

with

$$Z_0(x) = \sqrt{\frac{L(x)}{C(x)}}. \tag{35}$$

These transformations lead to the Zakharov-Shabat equations

$$\begin{aligned} \frac{d\nu_1(\omega, x)}{dx} + ik\nu_1(\omega, x) &= q^*(x)\nu_1(\omega, x) + q^+(x)\nu_2(\omega, x) \\ \frac{d\nu_2(\omega, x)}{dx} - ik\nu_2(\omega, x) &= q^-(x)\nu_1(\omega, x) - q^*(x)\nu_2(\omega, x) \end{aligned} \tag{36}$$

with

$$\begin{aligned} q^{\pm}(x) &= -\frac{1}{4}\frac{d}{dx}\left[ln\frac{L(x)}{C(x)}\right] \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right] \\ &= -\frac{1}{2Z_0(x)}\frac{d}{dx}Z_0(x) \mp \frac{1}{2}\left[\frac{R(x)}{L(x)} - \frac{G(x)}{C(x)}\right] \\ q^*(x) &= \frac{1}{2}\left[\frac{R(x)}{L(x)} + \frac{G(x)}{C(x)}\right]. \end{aligned} \tag{37}$$

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 (35), 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 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.

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.

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.

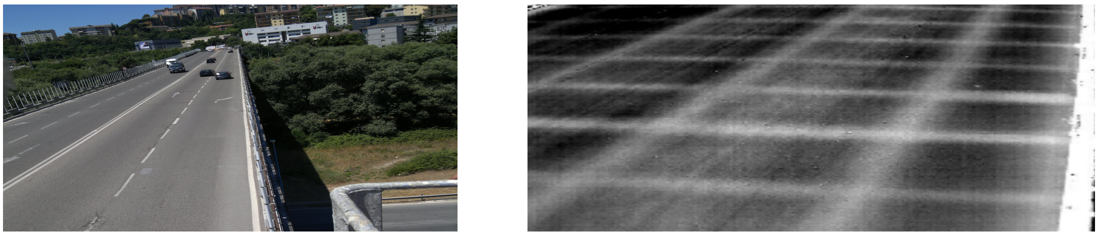

Figure 4. Left: Image in the visible spectrum of the deck surface - Right: PCT result on a bridge deck

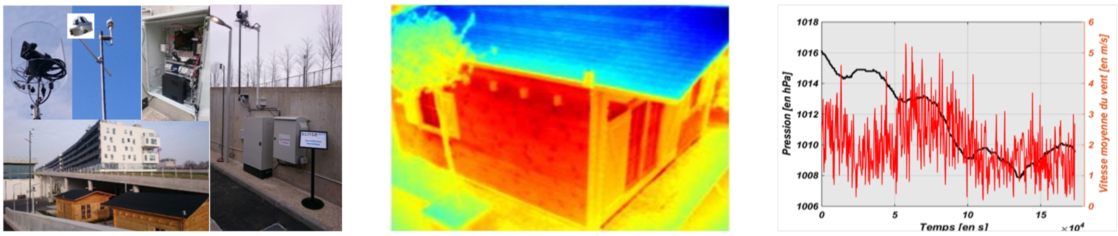

Figure 5. Various view and results of the SenseCity experimentation site - (site and hardware view, IR imaging, Environmental Monitoring)

Most of the innovations featured in R5G are now mature, for example communication and 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.

5. Highlights of the Year

5.1. Highlights of the Year

The Structual Health Monitoring system developed by Vincent Le Cam and SDEL-CC for lightning detection and localization on electrical lines, has received the VINCI Innovation Award for Western France 2017. https://team.inria.fr/i4s/vinci-2017-innovation-award/

5.1.1. Awards

BEST PAPERS AWARDS:

[29]

J. DUMOULIN, A. CRINIÈRE. *Infrared Thermography applied to transport infrastructures monitoring: outcomes and perspectives*, in "SPIE - Thermosense: Thermal Infrared Applications XXXIX", Anaheim California, United States, April 2017, https://hal.inria.fr/hal-01509555

[30]

M. DÖHLER, P. ANDERSEN, L. MEVEL. *Variance computation of modal parameter estimates from UPC subspace identification*, in "IOMAC - 7th International Operational Modal Analysis Conference", Ingolstadt, Germany, May 2017, https://hal.inria.fr/hal-01522137

6. New Software and Platforms

6.1. PEGASE

Plate-forme Experte Générique pour Applications Sans-fil Embarquées
KEYWORD: SHM (Structural Health Monitoring)
FUNCTIONAL DESCRIPTION: PEGASE is a generic high level wireless sensor platform. The main characteristics of PEGASE to reach this genericity are obtained by :

- Software genericity: use of a Linux embedded OS to make any developed application independent from the hardware, and to enable the user to manage the system without any physical 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 (e.g., sensing, 3G, Lora/Sigfox and Ethernet wireless communications, signal processing and relay control).
- Accurate time synchronization: based on an original GPS and PPS algorithm, PEGASE platform is one of few boards able to time-stamp data from sensors or any event with an accuracy of some micro-seconds Universal Time.

After the industrial exploitation of PEGASE 1 (hundreds are sold), PEGASE 2 and the future PEGASE 3 version maintain and extend the previous platform. Focus on main characteristics is subject of electronic research and development:

- embed a "Debian" Linux operating system able to be validated for critical applications (such as SHM applications)
- embed a module dedicated to energy autonomy, to harvest energy from solar cells while considering the dis/charge of Lithium battery
- integrate a 3D accelerometer based on a MEMs to propose motion applications (train detection by vibration for example)
- new original daughter boards for new wireless IOT industrial protocols: LorA and Sigfox
- convert the proposed SDK (Single Development Kit) fully from C to C++ language
- a generic embedded front-end development called Zeus able to manage time control of Linux enslaved to the UTC synchronization, applications manager, network manager (from WiFi, Lora to 3G...), ...

Since 2017, PEGASE 2 platform is also used as the support for some lectures given at University of Nantes.

Associated to PEGASE hardware platform, I4S has also designed and programmed a generic Cloud Supervisor that allows to manage wireless sensors. In 2017 this application has matured, and has been licensed to two companies for industrial exploitation and distribution (Stimio and Power-Lan).

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

6.2. TrackingMecaSysEvo

KEYWORDS: Particular filter - Kalman filter - Monte-Clarlo - Bayesian estimation - Vibrating system
FUNCTIONAL DESCRIPTION: Based on a IPKF (Interacting Particles and Kalman Filter) implementation, TrackingMecaSysEvo allow mechanical parameters traking over the time for a 1-2-3D vibrating model. The algorithme insure also, input force and ambiant noise estimation

- Participants: Antoine Crinière, Laurent Mevel and Subhamoy Sen
- Partner: IFSTTAR
- Contact: Laurent Mevel

7. New Results

7.1. Outdoor InfraRed Thermography

7.1.1. Joint thermal and electromagnetic diagnostics

Participants: Nicolas Le Touz, Jean Dumoulin.

In this study, we present an inversion approach to detect and localize inclusions in thick walls under natural solicitations. The approach is based on a preliminary analysis of surface temperature field evolution with time (for instance acquired by infrared thermography); subsequently, this analysis is improved by taking advantage of a priori information provided by ground penetrating radar reconstruction of the structure under investigation. In this way, it is possible to improve the accuracy of the images achievable with the standalone thermal reconstruction method in the case of quasiperiodic natural excitation. [19]

7.1.2. Long term monitoring of transport infrastructures: from deployment to standardization

Participants: Antoine Crinière, Jean Dumoulin, Laurent Mevel.

Long term monitoring of transport infrastructures by infrared thermography has been studied and tested on different structures. A first standalone infrared system architecture developed is presented and discussed. Results obtained with such system on different Civil Engineering structures are presented. Some data processing approaches and inverse thermal model for data analysis are introduced and discussed. Lessons learned from experiments carried out in outdoor with such system are listed and analyzed. Then, a new generation of infrared system architecture is proposed. Finally, conclusions and perspectives are addressed.[29], [46]

7.1.3. Infrared data reconstruction and calibration for long term monitoring

Participants: Thibaud Toullier, Jean Dumoulin, Laurent Mevel.

This study focuses on the evaluation and improvement of thermal instrumentation solutions for long-term monitoring of next-generation transport infrastructure. A test site was equipped with thermocouples and an infrared thermography system coupled with monitoring of environmental parameters. A method of spatial reconstruction of infrared images is presented. Measurement data acquired on site and then post-processed are analysed over time. A conclusion on the results achieved and prospects are proposed [48]

7.2. Data management of Smart territories and cities

Participants: Antoine Crinière, Jean Dumoulin.

Highly instrumented Smart-cities, which are now a common urban policies, are facing problems of management and storage of a large volume of data coming from an increasing number of sources. This study presents a data compression method by predictive coding of spatially correlated multi-source data based on reference selection and prediction by Kriging [47]

7.3. Smarts roads and R5G

7.3.1. Energy exchange modelization and infrared monitoring for hybrid pavement structure

Participants: Nicolas Le Touz, Thibaud Toullier, Jean Dumoulin.

In those studies, we evaluate by numerical modelling the energy inputs that could occur in a hybrid pavement structure with a semi-transparent or opaque wearing course bonded to a porous base layer, the seat of a heat transfer fluid circulation. The digital studies conducted propose a coupled resolution of various thermal phenomena: diffusion/convection in the case of an opaque surface drainage pavement, and diffusion/convection/radiation for a pavement with a semi-transparent surface. Coupled equation systems are solved numerically using the finite element method. This model was developed directly on a Matlab kernel. In a second time, laboratory experiments on small specimen were carried out and the surface temperature was monitored by infrared thermography. Results obtained are analyzed and performances of the numerical model for real scale outdoor application are discussed .[35], [34]

7.3.2. Phase change materials characterization

Participant: Jean Dumoulin.

In a costs reduction and comfort requirements context, the use of phase change materials (PCM) is a sustainable and economical answer. For transportation infrastructures and winter maintenance, they avoid ice occurrence or snow accumulation. Their characteristics, and more specifically, the solid to liquid phase transition temperature and enthalpy, are usually obtained through DSC. Raman spectroscopy can bring answers and information on their microstructures. The liquid to solid phase change was investigated on three PCM, a paraffin, formic acid and diluted formic acid. A comparison made on freezing temperature obtained through DSC, Raman spectroscopy associated with chemiometrics indicated a consistency between the methods. Raman spectroscopy coupled with multivariate data analysis allowed the identification of an additional specificity in the freezing process of the paraffin. All methods provided results consistent between each other, although some differences between literature and experimental freezing temperatures of the considered PCM were observed in all cases. [20], [53]

7.4. Methods for building performance assessment

7.4.1. Building performance assessment

Participants: Jordan Brouns, Alexandre Nassiopoulos.

Two additive thermal sources are generally not simultaneously distinguishable from the only observation of their effect on the heat balance. However, there are cases where information about the variation regularity of these sources is known. This is typically the case of convective internal gains in the building, for which the use scenarios create discontinuous inputs while heat gains relating to the air leakage are regular in time. In the present paper, we introduce a method aiming to distinguish heat sources using this a priori knowledge about their dynamics. We provide numerical and experimental evidence that the method succeeds in separating/distinguishing these kind of sources. This method could be applied to the identification of the occupancy rate for measurement and verification plans or smart home systems such as learning thermostats. [16]

7.5. System identification

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

Participants: Michael Doehler, Laurent Mevel.

This work has been carried out in collaboration with Palle Andersen.

Subspace-based system identification allows the accurate estimation of the modal parameters (natural frequencies, damping ratios, mode shapes) from output-only measurements, amongst others with data-driven methods like the Unweighted Principal Component (UPC) algorithm. Due to unknown excitation, measurement noise and finite measurements, all modal parameter estimates are inherently afflicted by uncertainty. The information on their uncertainty is most relevant to assess the quality of the modal parameter estimates, or when comparing modal parameters from different datasets. A method for variance estimation is presented for the variance computation of modal parameters for the UPC subspace algorithm. Developing the sensitivities of the modal parameters with respect to the output covariances, the uncertainty is propagated from the measurements to the modal parameters from UPC. The resulting variance expressions are easy to evaluate and computationally tractable when using an efficient implementation. In a second step, the uncertainty information of the stabilization diagram is used to extract appropriately weighted global mode estimates and their variance. The method is applied to experimental data from the Z24 Bridge [30].

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

Participants: Antoine Crinière, Laurent Mevel, Jean Dumoulin, Subhamoy Sen.

This work is in collaboration with F. Cerou of ASPI team at Inria.

Standard filtering techniques for structural parameter estimation assume that the input force either is known exactly or can be replicated using a known white Gaussian model. Unfortunately for structures subjected to seismic excitation, the input time history is unknown and also no previously known representative model is available. A novel algorithm is proposed to estimate the force as additional state in parallel to the system parameters. Two concurrent filters are employed for parameters and force respectively, mixing interacting Particle Kalman filter and another filter employed to estimate the seismic force acting on the structure [38], [49].

7.5.3. From structurally independent local LTI models to LPV model

Participant: Qinghua Zhang.

This work on linear parameter varying (LPV) system identification has been carried out in collaboration with Lennart Ljung (Linköping University, Sweden).

The local approach to LPV system identification consists in interpolating individually estimated local linear time invariant (LTI) models corresponding to fixed values of the scheduling variable. It is shown in this work that, without any global structural assumption of the considered LPV system, individually estimated local state-space LTI models do not contain sufficient information for determining similarity transformations making them coherent. Nevertheless, it is possible to estimate these similarity transformations from input-output data under appropriate excitation conditions [21].

7.5.4. Stability of the Kalman filter for output error systems

Participant: Qinghua Zhang.

The stability of the Kalman filter is classically ensured by the uniform complete controllability regarding the process noise and the uniform complete observability of linear time varying systems. Recently we have studied the stability of the Kalman filter for output error (OE) systems, in which the process noise is totally absent. In this case the classical stability analysis assuming the controllability regarding the process noise is thus not applicable. Our first efforts were focused on continuous time systems, whereas discrete time systems have been studied since last year. It is shown in this work that the uniform complete observability is sufficient to ensure the stability of the Kalman filter applied to time varying OE systems, regardless of the stability of the OE systems [22].

7.5.5. Reduced-order interval-observer design for dynamic systems with time-invariant uncertainty

Participant: Qinghua Zhang.

This work on interval-based state estimation has been carried out in collaboration with Vicenç Puig's team (Universitat Politècnica de Catalunya, Spain). The reported work addresses in particular the design of reduced-order interval-observers for dynamic systems with both time-invariant and time varying uncertainties. Because of the limitations of the set-based approach and the wrapping effect to deal with interval-observers, the trajectory-based interval-observer approach is used with an appropriate observer gain. Due to difficulties to satisfy the conditions for selecting a suitable gain to guarantee the positivity of the resulting observer, a reduced-order observer is designed to increase the degree of freedom when selecting the observer gain and to reduce the computational complexity. Simulation examples illustrates the effectiveness of the proposed approach [37].

7.5.6. 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).

Recently, a subspace fitting approach has been proposed for vibration-based finite element model updating. The approach makes use of subspace-based system identification, where the extended observability matrix is estimated from vibration measurements. Finite element model updating is performed by correlating the model-based observability matrix with the estimated one. However, estimates from vibration measurements are inherently exposed to uncertainty. A covariance estimation procedure for the updated model parameters is proposed, which propagates the data-related covariance to the updated model 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. Simulated vibration signals and experimental data of a beam validate the method [18].

7.6. Damage diagnosis

7.6.1. Damage detection by perturbation analysis and additive change detection theory

Participants: Michael Doehler, Laurent Mevel, Qinghua Zhang.

The monitoring of mechanical systems aims at detecting damages at an early stage, in general by using output-only vibration measurements under ambient excitation. In this paper, a method is proposed for the detection and isolation of small changes in the physical parameters of a linear mechanical system. Based on a recent work where the multiplicative change detection problem is transformed to an additive one by means of perturbation analysis, changes in the eigenvalues and eigenvectors of the mechanical system are considered in the first step. In a second step, these changes are related to physical parameters of the mechanical system. Finally, another transformation further simplifies the detection and isolation problem into the framework of a linear regression subject to additive white Gaussian noises, leading to a numerically efficient solution of the considered problems. A numerical example of a simulated mechanical structure is reported for damage detection and localization [31].

7.6.2. Damage localization using the statistical subspace damage localization method

Participants: Michael Doehler, Laurent Mevel, Saeid Allahdadian.

This work is happening during a thesis in collaboration with C. Ventura at UBC, Vancouver.

In this paper the statistical subspace damage localization (SSDL) method is employed in localizing the damage in a real structure, namely the Yellow frame. The SSDL method is developed for real testing conditions and tested in two damage configurations. It was demonstrated that the SSDL method can localize the damage robustly in the Yellow frame for simple and multiple distinct damage scenarios using the analytical modal parameters. The method is described and its effectiveness is demonstrated [24].

7.6.3. Stochastic Subspace-Based Damage Detection with Uncertainty in the Reference Null Space

Participants: Michael Doehler, Laurent Mevel, Eva Viefhues.

This work is happening during a thesis in collaboration with F. Hille at BAM, Berlin.

This paper deals with uncertainty considerations in damage diagnosis using the stochastic subspace-based damage detection technique. With this method, a model is estimated from data in a (healthy) reference state and confronted to measurement data from the possibly damaged state in a hypothesis test. Previously, only the uncertainty related to the measurement data was considered in this test, whereas the uncertainty in the estimation of the reference model has not been considered. We derive a new test framework, which takes into account both the uncertainties in the estimation of the reference model as well as the uncertainties related to the measurement data. Perturbation theory is applied to obtain the relevant covariances. In a numerical study the effect of the new computation is shown, when the reference model is estimated with different accuracies, and the performance of the hypothesis tests is evaluated for small damages. Using the derived covariance scheme increases the probability of detection when the reference model estimate is subject to high uncertainty, leading to a more reliable test [41].

7.6.4. Statistical damage localization with stochastic load vectors

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

This work is in collaboration with F. Schoefs and Y. Lecieux, GEM, Nantes.

The Stochastic Dynamic Damage Locating Vector (SDDLV) method is a damage localization method based on both a Finite Element (FE) model of the structure and modal parameters estimated from 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 from 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. An important theoretical limitation was that the number of modes used in the computation could not be higher than the number of sensors located on the structure. In this paper, the SDDLV method has been extended with a joint statistical approach for multiple mode sets, overcoming this restriction on the number of modes. Another problem is that the performance of the method can change considerably depending of the Laplace variable where the transfer function is evaluated. Particular attention is given to this choice and how to optimize it. The new approach is validated in numerical simulations and on experimental data. 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 [15], [52], [27].

7.6.5. Transfer matrices-based statistical damage localization and quantification

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

This work is in collaboration with GEM, Nantes and C. Ventura at UBC, Nantes.

Vibration measurements and a finite element model are used to locate loss of stiffness in a steel frame structure at the University of British Columbia. The Stochastic Dynamic Damage Locating Vector (SDDLV) is compared to a sensitivity based approach developed by the authors. Both approaches have in common to be built on the estimated transfer matrix difference between reference and damaged states. Both methods are tested for localization and quantification on a structure at University of British Columbia [26], [28].

7.6.6. Statistical damage localization based on Mahalanobis distance

Participant: Michael Doehler.

This work is in collaboration with Aalborg University, Structural Vibration Solutions and Universal Foundation in Denmark during the thesis of S. Gres (Aalborg University).

In this paper, a new Mahalanobis distance-based damage detection method is studied and compared to the wellknown subspace-based damage detection algorithm. Methods are implemented using control charts to enhance the resolution of the damage detection. The damage indicators are evaluated based on the ambient vibration signals from numerical simulations on a novel offshore support structure and experimental example of a full scale bridge. The results reveal that the performance of the two damage detection methods is similar, hereby implying merit of the new Mahalanobis distance-based approach, as it is less computationaly complex [32].

7.6.7. On the value of Information for SHM

Participant: Michael Doehler.

This work is issued from the COST Action TU1402.

The concept of value of information (VoI) enables quantification of the benefits provided by structural health monitoring (SHM) systems in principle. Its implementation is challenging, as it requires an explicit modelling of the structural system's life cycle, in particular of the decisions that are taken based on the SHM information. In this paper, we approach the VoI analysis through an influence diagram (ID), which supports the modelling process. We provide a simple example for illustration and discuss challenges associated with real-life implementation [39].

7.6.8. Structural system reliability and damage detection information

Participant: Michael Doehler.

This work is in collaboration with S. Thöns (DTU) during the thesis of L. Long (BAM).

This paper addresses the quantification of the value of damage detection system and algorithm information on the basis of Value of Information (VoI) analysis to enhance the benefit of damage detection information by providing the basis for its optimization before it is performed and implemented. The approach of the quantification the value of damage detection information builds upon the Bayesian decision theory facilitating the utilization of damage detection performance models, which describe the information and its precision on structural system level, facilitating actions to ensure the structural integrity and facilitating to describe the structural system performance and its functionality throughout the service life. The structural system performance is described with its functionality, its deterioration and its behavior under extreme loading. The structural system reliability given the damage detection information is determined utilizing Bayesian updating. The damage detection performance is described with the probability of indication for different component and system damage states taking into account type 1 and type 2 errors. The value of damage detection information is then calculated as the difference between the expected benefits and risks utilizing the damage detection information or not. With an application example of the developed approach based on a deteriorating Pratt truss system, the value of damage detection information is determined, demonstrating the potential of risk reduction and expected cost reduction [36].

7.6.9. Estimation of a cable resistance profile with readaptation of mismatched measurement instrument

Participants: Nassif Berrabah, Qinghua Zhang.

As the cumulative length of electric cables in modern systems is growing and as these systems age, it becomes of crucial importance to develop efficient tools to monitor the condition of wired connections. Therein, in contrast to hard faults (open or short circuits), the diagnosis of soft-faults requires a particular effort. Indeed, these faults are more difficult to detect, yet they are sometimes early warning signs of more important failures. In a previous paper, we proposed a method to compute the resistance profile of a cable from reflectometry measurements made at both ends of the cable. It enables detection, localization and estimation of dissipative soft-faults. In this reported work, we address the problem of impedance mismatch between the measurement instrument and the cable, based on a pre-processing of the measured data before running the estimation computations. It aims at reducing the impedance mismatch between instrumentation and the cable under test without physical intervention on the test fixtures. In addition, a measurement procedure has been developed in order to get the two-ends reflectometry measurements without actually connecting both ends of the cable under test to a single instrument [25].

7.7. Sensor and hardware based research

7.7.1. Cracks detection in pavement by a distributed fiber optic sensing technology

Participant: Xavier Chapeleau.

This paper presents the feasibility of damage detection in asphalt pavements by embedded fiber optics as a new non-destructive inspection technique. The distributed fiber optic sensing technology based on the Rayleigh scattering was used in this study. The main advantage of this technique is that it allows to measure strains over a long length of fiber optic with a high spatial resolution, less than 1 cm. By comparing strain profiles measured at different times, an attempt was made to link strain changes with the appearance of damage (cracking) in the pavement. This non-destructive method was evaluated on accelerated pavement testing facility, in a bituminous pavement. In our experimentation, the optical fibers were placed near the bottom of the asphalt layer. The application of 728 000 heavy vehicle loads (65 kN dual wheel loads) was simulated in the experiment. Optical fiber measurements were made at regular intervals and surface cracking of the pavement was surveyed. After some traffic, a significant increase of strains was detected by the optical fibers at different points in the pavement structure, before any damage was visible. Later, cracking developed in the zones where the strain profiles were modified, thus indicating a clear relationship between the increased strains and crack initiation. These first tests demonstrate that distributed fiber optic sensors based on Rayleigh scattering can be used to detect crack initiation and propagation in pavements, by monitoring strain profiles in the bituminous layers [17].

7.7.2. Wireless sensors and GPS synchronization

Participants: Vincent Le Cam, David Pallier.

Most of recent development in WSN domain focused on energy (saving or harvesting), on wireless protocols, on embedded algorithms. But it is a fact that, most of monitoring applications need samples to be time-stamped. According to the application, the wished time resolution could be up to one second for automation monitoring, one millisecond for vibration, one microsecond for acoustic monitoring, one nanosecond for electricity or light propagation... The consequence for a Wireless network of electronic nodes is that, by nature, no common signal could physically provide a synchronization top. But, as each electronic device, a wireless sensor time-base uses a timer incremented by a quartz whose initial value is theoretical up to some p.p.m. and whose period drift on time because of age, temperature,... Two kind of solutions could be regarded : a synchronization signal provided by the wireless protocol itself; an absolute synchronization from a referential source such as: GPS, Frankfurt clock, Galileo,... In the first way, it will be demonstrated the poor accuracy and the need of energy such a mechanism offers. In the second way, the article will details how a deterministic (Universal Time), accurate and resilient algorithm has been implemented. The article also provides specific results of application on acoustic monitoring system and electricity propagation where the accuracy of a WSN has reached up to 10 nanosecond UT. Consequence on energy consumption of this algorithm are given with a description of future works to improve the energy balance while keeping the device sober and synchronized [33].

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. 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.

In 2017, a new Innobooster grant has been obtained for the uncertainty analysis of mode shapes in Artemis.

8.1.2. Contract with SNCF: DEMETER

Participants: Vincent Le Cam, Quentin Bossard, Mathieu Le Pen.

IFSTTAR's engineers Arthur Bouche and Laurent Lemarchand are contributing to this project.

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 railway 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 wireless and smart sensor is designed (that may or may not use PEGASE 2 platform), installed along railway lines in service and data are transmitted wirelessly to the cloud supervisor at IFSTTAR for evaluation in SHM algorithms.

In particular, during 2017 SNCF and IFSTTAR have performed following common works:

- finalization of the TRAIN PEDAL DETECTION instrumentation with smart sensors using new wireless and industrial IOT protocoles: LoRa and Sigfox. A specific pedal is now subject of in situ test led by SNCF
- axel counter monitoring has been the major R&D subject of 2017: 2 entire and specific smart sensors have been designed, programmed and installed at Chevilly specific SNCF testbench (e.g. with real train passages). Specific algorithms (such as PID and Pattern Recognition) have been modeled and programmed into PEGASE2 platform for these new sensors.

For the future, new projects related to

- water-level monitoring around railways has been setup
- ballast vibration monitoring of railways has been setup
- "unshunting of electrical lines at train passage" detection around railways

have been initiated with SNCF R&D department.

8.1.3. *Contracts with SDEL-CC (VINCI Group)*

Participants: Vincent Le Cam, Mathieu Le Pen.

This work was done in collaboration with Laurent Lemarchand, and Arthur Bouche at IFSTTAR, SII, Nantes.

Following a 2016 contract, a new contract was signed in 2017 until end 2018, with the company SDEL-CC, a 100% daughter of the VINCI Group, Energy department. The project exploits the unique time stamp capacity of the PEGASE 2 platform up to 50 nanoseconds, independently of distances in the network of PEGASE2 nodes. The synchronization capacity is employed to design a sensor prototype based on PEGASE 2 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.

During 2017, a real high-voltage electrical line has been instrumented: at each end of the line, 2 sensors have been set up and data are sent in real time to a cloud platform. Furthermore, the software of the platform was optimized: at the embedded level (i.e. on PEGASE 2 wireless system) with new algorithms to correct time synchronization up to some 10 nanoseconds, at the cloud level with a specific QT C++ Interface to display results (i.e. lightning localization on electrical line) and to transform raw data into ComTrade standard representation

Discussions are ongoing with SDEL-CC to transform the prototype into a future product. In 2017 it has to be mentioned that the project has been submitted to VINCI International challenges (over 150 000 collaborators) and has been awarded with The Best Vinci Innovation Award.

8.2. Bilateral Grants with Industry

8.2.1. *PhD project with EDF – Electrical device ageing monitoring*

Participants: Nassif Berrabah, Qinghua Zhang.

A joint PhD project between Inria and EDF (Electricité de France) was started in December 2014 and finished in November 2017 with Nassif Berrabah's PhD thesis defense. 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 has been funded by EDF and by the ANRT agency. The main outcome of this project is an efficient reflectometry-based method for resistive fault detection, localization and quantification, capable of dealing with both distributed and localized faults, with associated data processing tools taking into account practical constraints in industrial applications. These results have led to a patent jointly filed by EDF and Inria.

9. Partnerships and Cooperations

9.1. Regional Initiatives

9.1.1. MONEOL

Participants: Ivan Guéguen, Guillaume Gautier, Laurent Mevel.

Type: CEAtech PDL

Objectif: Modal analysis of wind turbines using new sensors

Duration: 09/2015 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.

The MONEOL (Wind turbine monitoring) project was concluded in September 2017. Morphosense ribbon was deployed on the mast of a wind turbine. Morphosense validation was conducted through the comparison with a classical vibration monitoring system. The relevance regarding the use of such a system was highlighted, especially due to reduced installation time. SSI algorithms, including modal parameters and damage identification, were implemented inside the Morphosense. Actually, wind turbine health condition is displayed in real time through a web page.

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

Participants: Jean Dumoulin, Antoine Crinière, Frederic Gillot.

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. In collaboration with Nantes Métropole, CSTB, and Université de Nantes, instrumentation of both dynamical and InfraRed properties of an operational bridge are investigated. These measures coupled with a wireless data transmission system will allow remote monitoring of the evolution of the structure. Objective is to couple different kind of measurement to achieve thermo-vibration monitoring of the structure. This is a big milestone for the team and our objective to mix thermo-vibration data.

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

Participants: Xavier Chapeleau, Ivan Guéguen.

Type: GIS

Objectif: MOnitoring of Structural Integrity of an onshore WIND turbine 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 turbineâs 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. Since July 2017, only the data of accelerometers measurements are logged periodically. The installation of systems of measurements for distributed fiber optics sensors and optical strains gauges remains to be done as soon as it can be possible to access to the wind turbine .

9.1.5. Collaboration with GeM

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

Md Delwar Hossain Bhuyan has done his PhD on damage localisation on civil structures in collaboration with GeM (Institute of Civil and Mechanical Engineering), Université de Nantes. The thesis is co-directed by L. Mevel, and F. Schoefs from GeM, with supervision shared with M. Doehler and Y. Lecieux from GeM. It is funded by the Brittany region for 3 years and has been successfully defended in November 2017.

9.1.6. Collaboration with IETR

Participants: Vincent Le Cam, David Pallier.

The thesis is directed by Sébastien Pillement at IETR. It is funded by RFI WISE Electronique Professionnelle within the SENTAUR project.

The subject of the thesis is to study, implement and propose a deterministic and reliable dating solution for wireless sensor networks. This solution must take into account both the risks of loss of synchronization signals, environmental hazards and the desire to achieve the most sober possible solution in energy.

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 to orchestrate multiple sections of a high-speed route (classical section with granular layer, transition zone). The proposed instrumentation concerns all the different layers of the structure, and is designed to allow monitoring of the overall track behavior. Using accelerometers and weather station, this instrumentation will estimate the fatigue life and temperature changes in the track.

9.2.2. ANR Resbati

Participants: Ludovic Gaverina, 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: RESBATI is an applied research project whose objective is to develop a field measurement device that meets precise specifications to systematically measure the level of thermal insulation of building walls. The preferred metrological tool is infrared thermography.

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)

Participant: Jean Dumoulin.

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 involving 20 European partners that seeks to reduce the gap between a building designed and as-built energy performance. To do this, the project put a new set of breakthrough technological advances for self-inspection checks and quality assurance measures into the hands of construction professionals. The project aims to deliver Building Information Modelling (BIM) and Thermal and 3D Imaging Tools among others.

The project is in collaboration with formers members of the team, Alexandre Nassiopoulos and Jordan Brouns, now working at Ecotropy, SME.

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

Participants: Xavier Chapeleau, Antoine Bassil.

Call: H2020-MSCA-ITN-2015 (Horizon 2020 â Marie-Sklodowska Curie Actions â 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. During the first 6 months of the thesis, a State of the Art on the use of fiber optic sensors for structural health monitoring in civil engineering was done and mostly by focusing on distributed optical fiber sensor’s technology (DOFS) for crack detection in concrete. This State of the Art shows that distributed optical fiber sensor can localize accurately cracks in concrete if they propagate across the sensor. However, the quantification of the crack widths by distributed optical fiber sensor remains a scientific challenge. Indeed, it is necessary to take into account of the mechanical strain transfer of the fiber sensor. Now, the second part of the phd student work is to develop a theoretical model for the mechanical strain transfer function and to validate it by experimental tests. The main milestone of the modelling to overcome is to take into account of slippage and elasto-plastic effects

9.3.2. Collaborations in European Programs, Except FP7 & H2020

9.3.2.1. 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: Since 2014, until 2018, the COST Action has altogether around 120 participants from over 25 countries. This Action 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. Progress of the action is presented in [40].

9.3.2.2. PROCOPE 37826QE

Participants: Michael Doehler, Laurent Mevel, Eva Viefhues.

Type: PHC PROCOPE

Objectif: Statistical damage localization for civil structures

Duration: 01/2017 - 12/2018

Coordinator: M. Doehler

Partner: BAM German Federal Institute for Materials Research and Testing

Inria contact: M. Doehler

Abstract: Our main objective is the development of a theoretically solid damage localization method that does not only work in simulations and lab experiments, but on structures in the field under real operational conditions. This German-French mobility grant is in support of Eva Viefhues' PhD thesis.

9.3.3. Collaborations with Major European Organizations

9.3.3.1. 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.

9.3.4. Other European Programs

9.3.4.1. Innobooster

Participants: Michael Doehler, Laurent Mevel.

Together with SVS, we got the Danish Innobooster innovation grant for industrial research and transfer. In 2017, the grant was awarded to transfer methods for the identification of mode shapes and their uncertainty [30] to SVS' ARTeMIS software.

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. A proposal for associated lab is currently drafted.

9.4.1.2. Collaboration with British Columbia University, Canada

Participants: Laurent Mevel, Michael Doehler, Saeid Allahdadian.

Saeid Allahdadian was 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. The thesis has been defended this year.

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, Francesco Giordano.

During COST Action TU 1402 and professor M.P. Limongelli's research stay at IFSTTAR, collaboration with Politecnico di Milano has started, resulting in several joint publications in 2016 and 2017. PhD student F. Giordano has started at Politecnico Milano in November 2017 under the direction of M.P. Limongelli, M. Doehler is co-supervising.

9.4.1.5. Collaboration with Technical University of Denmark (DTU)

Participant: Michael Doehler.

During COST Action TU 1402 and previously at BAM, collaboration with Sebastian Thöns from DTU in Denmark started on risk analysis and SHM based reliability updating. Also, DTU's PhD student Lijia Long is involved [36].

9.4.1.6. Collaboration with Aalborg University, Denmark

Participant: Michael Doehler.

Together with Structural Vibration Solutions, collaboration with Aalborg University (professor Lars Damkilde, Department of Civil Engineering) has started during the PhD of Szymon Gres on damage detection methods [32].

9.5. International Research Visitors

9.5.1. Visits of International Scientists

Within the PROCOPE mobility grant, E. Viefhues and F. Hille from BAM, Germany, visited Inria for one week each.

Prof. Xingwen Liu from Southwest University of China visited the I4S team for one week.

9.5.2. Visits to International Teams

Within the PROCOPE mobility grant and the collaboration in L. Long's PhD thesis with S. Thöns, M. Doehler spent 4 weeks at BAM, Germany.

Within the IFSTTAR foreign affair department grant and the existing collaboration, J. Dumoulin spent 2 weeks at Laval University, Canada.

Within the H2020 INFRASTAR Project A. Bassil spent 3 months at BAM.

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 2017 (http://www.egu2017.eu/).

Q. Zhang is

- member of the international program commitee of the 18th IFAC Symposium SYSID that will take place in Stockholm, Sweden, July 9-11, 2018.
- member of the international program commitee of the 10th IFAC Symposium SAFEPROCESS that will take place in Warsaw, Poland, 29-31 August 2018.
- 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.
- member of IFAC Technical Committee on Adaptive and Learning Systems.

L. Mevel is

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

V. Le Cam is

- member of the IWSHM scientific committee.
- head and general secretary of the EWSHM scientific committee.

M. Doehler is member of IFAC Technical Committee on Modelling, Identification, and Signal Processing.

10.1.1.2. Reviewer

V. Le Cam was session chairman for IWSHM 2017 in Stanford

L. Mevel was session chairman for IWSHM 2017 in Stanford

Q. Zhang was reviewer for CDC 2017, ACC 2018.

M. Doehler was was session organizer at a COST workshop (http://www.cost-tu1402.eu/), session chairman at IOMAC 2017, and reviewer for ACC 2018.

J. Dumoulin was reviewer for QIRT ASIA 2017 and session chairman at EGU 2017 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 the journal Mathematical Problems in Engineering, and of the journal 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 Quantitative Infrared Thermography, and of the journal Geoscientific Instrumentation and Data Systems.

10.1.2.2. Reviewer - Reviewing Activities

L. Mevel was reviewer for Mechanical Systems and Signal Processing, journal of Sound And Vibration, Sensors, Advanced Engineering Informatics, Structural Control and Health Monitoring, Advances in Structural Engineering

M. Doehler was reviewer for Automatica, Mechanical Systems and Signal Processing, Journal of Sound and Vibration, Journal of Testing and Evaluation

J. Dumoulin was reviewer for Quantitative Infrared Thermography Journal, GI Journal (EGU), SFT conference, ASME New NDE Journal

F. Gillot was reviewer for Structural and Multidisciplinary Optimization, Applied Mathematical Modelling, Shock and Vibration, Applied Sciences

10.1.3. Invited Talks

M. Doehler and L. Mevel, “Méthodes statistiques pour l’analyse vibratoire des structures,” Journée scientifique Évaluation non destructive dans le génie civil de l’énergie, Nantes, France

M. Doehler, “Subspace-based methods for damage assessment,” Wölfel Engineering, Würzburg, Germany

J. Dumoulin, “Infrared thermography in civil engineering: from non destructive testing in laboratory to outdoor thermal monitoring”, QIRT ASIA 2017, Daejeon, Soth Korea

N. Le Touz, J. Dumoulin and J-M. Piau, “ Etude et développement d’un modèle EF de transfert de chaleur multi-physique : application à l’étude de routes solaires hybrides”, Journée thématique du groupe rayonnement de la société Française de Thermique sur “Méthodes numériques pour la résolution de l’équation de transfert radiatif : développements récents, modèles, et objectifs”, Paris, France

V. Le Cam, "Internet of Things and new chalenges for Transportation and Structural Monitoring", plenary talk given to Committee of Transport Minestry, on 25 january 2017, to CEA List, on 16th March 2017, and to assembly of COFREND (500 people) on 30th May 2017

10.1.4. Research Administration

V. Le Cam is member of the scientific council of WEN (West Electronic Network) since 2014, which is a cluster of about 200 companies, academics and research laboratories active in electronics. During 2017, he has been involved amongst others in meetings and selection of R&D projects, PhD and post-doc funding, international mobility.

M. Doehler was reviewer of a research proposal submitted to the Polish National Science Centre (national research agency).

10.2. Teaching - Supervision - Juries

10.2.1. Teaching

J. Dumoulin

- Licence Professionnelle TAM : thermographie infrarouge active, 16h, Université Paris-Est, France
- Master 2 MMMRI (Maintenance et Maîtrise des Risques Industriels), contrôle non destructif par thermographie infrarouge active, 12h, Université Paris-Est, France
- Master 2 ITII, 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), France.
- Conference course, 2h, IR inspection of infrastructures: Scope of application, technical solutions and analysis methods, QIRT ASIA 2017, Daejeon, South Korea

V. Le Cam

- Master 2 Civil engineering, Structural Monitoring, 4h, Université de Nantes, France
- Licence 3 Professional SEICOM, 3h of theoretical lessons and 20H of practical lessons on Embedded and Smart Systems, Université de Nantes, France
- ESEO, 16h, practical lessons on embedded and smart systems under Linux, France
- Master 2 Electrical Engineering (GEII), 4h on electronic systems and Structural Monitoring, Université Bretagne Sud, France

M. Doehler

- Master 1 informatique, 24 TD projet recherche, Université de Rennes 1 & ENS Rennes, France
- Cycle préparatoire intégré, STPI, mathématiques, 96h TD, INSA Rennes, France
- Conference course, 2h, Advanced Operational Modal Analysis using Stochastic Subspace Identification and its Applications, IOMAC 2017, Ingolstadt, Germany

X. Chapeleau

- Licence Pro Mesures physiques, Mesures optiques, 15h, IUT de St Nazaire, Université de Nantes, France

T. Toullier

- Master 1, TP Capteurs (12h), contrôle, commandes, École Centrale de Nantes, France
- Foundation Master, TD Programming and Data Analysis (14h), École Centrale de Nantes, France

F. Gillot

- Master 1, Conception optimale robuste de systèmes mécaniques (10h), École Centrale de Lyon, France
- Master 1, Dynamique des systèmes biologiques humains (4h), École Centrale de Lyon, France
- Formation initiale des ingénieurs de l'École Centrale de Lyon, TP, TD, BE, niveau L3, (50h), 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 for civil structures*, L. Mevel, F. Schoefs, Y. Lecieux and M. Doehler. Ecole doctorale MathSTIC, Université de Rennes 1, defended in 2017.

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

Shubamoy Sen's post-doctoral project on seismic event monitoring, L. Mevel, 2016-2017.

Guillaume Gautier's post-doctoral project on seismic event monitoring, L. Mevel, 2017-2018.

Ludovic Gavérina post-doctoral project on in-situ measurement of thermal resistance of building envelopes, J. Dumoulin, march 2017- february 2019.

PhD : Nassif Berrabah, Electrical cable ageing monitoring , Q. Zhang, Ecole doctorale MathSTIC, Université de Rennes 1, defended in 2017.

PhD : Nicolas Le Touz. *Design and study of positive energy transport infrastructures: from thermomechanical modeling to the optimization of such energy systems* J. Dumoulin. Ecole Centrale Nantes (ECN) since december 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 MathSTIC, Université de Rennes 1, since November 2016.

PhD : Saeid Allahdadian, *Methods for vibration-based damage assessment*, M. Doehler and C. Ventura. University of British Columbia, Canada, defended in 2017.

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

PhD : Francesco Giordano, *Value of information for strain monitoring of infrastructure*, M. Doehler and MP. Limongelli and F. Bourquin. Politecnico Milano, Italy, since November 2017.

PhD : David Pallier, *Sensor Enhancement to Augmented Usage and Reliability*, S. Pillement, IETR, V. Le Cam, Ecole doctorale MathSTIC

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

M. Doehler is associate researcher at BAM, Germany.

10.2.3. Juries

Jean Dumoulin was invited jury member for the PhD defense of Yingying YANG at I2M in Bordeaux.

10.3. Popularization

The Hybrid solar road Mock-up (presented at the French Pavillon during COP21) has been invited and presented at:

- Forum National des Travaux Publics, Carroussel du Louvre (Paris), February 2017
- Innovation day des Travaux Publics, Casino du Lyon Vert (Lyon), December 2017
- Fête de la science, Ecole d'architecture de Nantes, October 2017

11. Bibliography

Major publications by the team in recent years

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[2] A. Crinière, J. Dumoulin, C. Ibarra-Castanedo, X. Maldague. *Inverse model for defect characterisation of externally glued CFRP on reinforced concrete structures: comparative study of square pulsed and pulsed thermography*, in "Quantitative InfraRed Thermography Journal", March 2014, vol. 11, n^{o} 1, pp. 84-114 [*DOI :* 10.1080/17686733.2014.897512], https://hal.archives-ouvertes.fr/hal-01081174

[3] J. Dumoulin, V. Boucher. *Infrared thermography system for transport infrastructures survey with inline local atmospheric parameter measurements and offline model for radiation attenuation evaluations*, in "Journal of Applied Remote Sensing", 2014, vol. 8, n^{o} 1, pp. 084978–084978

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Publications of the year

Articles in International Peer-Reviewed Journals

[15] M. D. H. BHUYAN, M. DÖHLER, Y. LECIEUX, L. MEVEL, F. SCHOEFS. *Statistical damage localization with stochastic load vectors using multiple mode sets*, in "Structural Health Monitoring", August 2017, vol. 16, n^{o} 5, pp. 518-535 [*DOI :* 10.1177/1475921717714447], https://hal.inria.fr/hal-01577250

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Invited Conferences

[23] J. DUMOULIN. *Infrared Thermography in Civil Engineering: From Non Destructive Testing in Laboratory to Outdoor Thermal Monitoring*, in "QIRT-Asia 2017 - 2nd Asian Conference on Quantitative InfraRed Thermography", Daejeon, South Korea, July 2017, https://hal.inria.fr/hal-01651932

International Conferences with Proceedings

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