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Université Gustave Eiffel

Activity Report 2019

Project-Team I4S

Statistical Inference for Structural Health Monitoring

RESEARCH CENTER
Rennes - Bretagne-Atlantique

THEME
Optimization and control of dynamic systems

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2. Overall Objectives

2.1. Overall Objectives

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 :

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

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

Subspace-based methods is the generic name for linear systems identification algorithms based on either time domain measurements or output covariance matrices, in which different subspaces of Gaussian random vectors play a key role [51].

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

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

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

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

where:

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

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

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

3.1.2. Detection

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

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

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

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

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

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

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

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

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

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

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

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

3.1.2.1. Residual associated with subspace identification.

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

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

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 [45] that the residual is asymptotically Gaussian :

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

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 :

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

where

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

3.1.3. Diagnostics

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

The question: *which (subsets of) components of θ have changed ?*, can be addressed using either nuisance parameters elimination methods or a multiple hypotheses testing approach [44].

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 introduces 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 μm and 1 mm, this range begin in uv spectrum and it ends on the microwaves domain, see Figure 1.

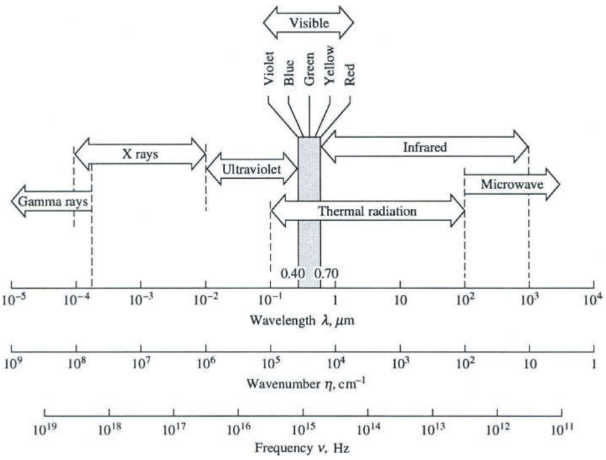

Figure 1. Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

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

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

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

Our work is concentrated in the mid infrared spectral band. Keep in mind that Table 1 represents the ISO 20473 division scheme, in the literature boundaries between bands can move slightly.
The Plank's law, proposed by Max Planck 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 and C_2 constants, respectively in $W.m^2$ and m.K are defined as follow:

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

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.

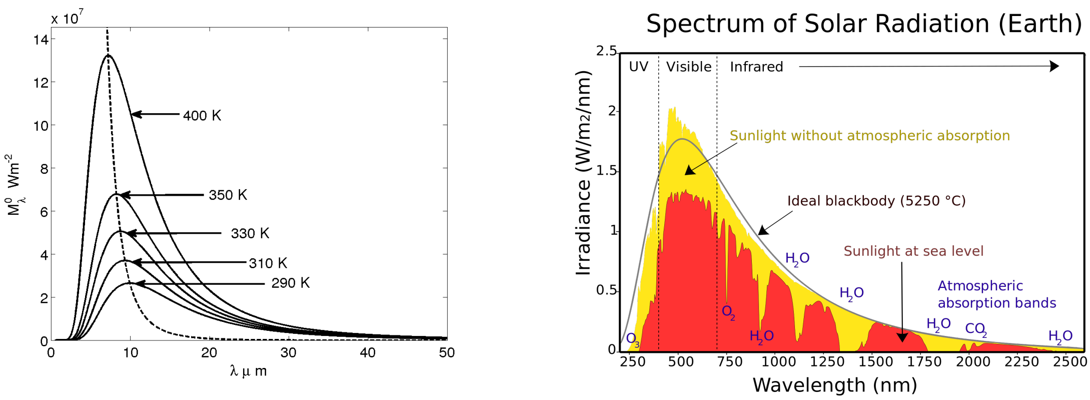

Figure 2. Left: Plank's law at various temperatures - Right: Energy spectrum of the atmosphere

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 depending on 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 purposes, 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 yields 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...), otherwise 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, model inversion is used, 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 yields 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 to 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 cases 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 with respect to the 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 the external heat flux has to be estimated, 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).

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

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], [50]. 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 [52], [48]. The main results concern, on the one hand, simple star-shaped networks from measurements made at a single node, on the other hand, complex networks of arbitrary topological structure with complete node observations.

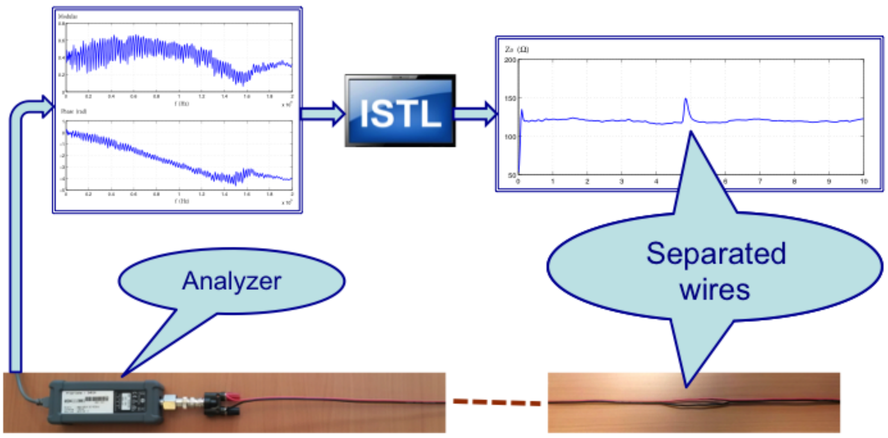

Figure 3. Inverse scattering software (ISTL) for cable soft fault diagnosis.

Though initially our studies on reflectometry were aiming at applications in electrical engineering, 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 [49]

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

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

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

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

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

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 [47]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [46]. After having completed some theoretic results directly linked to practice [14], [50], 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 fiber-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 fiber-reinforced polymer (CFRP) sheets and the glue layer thickness are designed by civil engineers to address strengthening objectives. Moreover, professional crews have to be trained accordingly in order to ensure the durability and long-term performance of the FRP reinforcements. Conformity checking through an 'in situ' verification of the bonded FRP systems is then highly desirable. The quality control programme should involve a set of adequate inspections and tests. Visual inspection and acoustic sounding (hammer tap) are commonly used to detect delaminations (disbonds). Nevertheless, these techniques are unable to provide sufficient information about the depth (in case of multilayered composite) and width of the disbonded areas. They are also incapable of evaluating the degree of adhesion between the FRP and the substrate (partial delamination, damage of the resin and poor mechanical properties of the resin). Consequently, rapid and efficient inspection methods are required. Among the non-destructive (NDT) methods currently under study, active infrared thermography is investigated due to its ability to be used in the field. In such context and to reach the aim of having an in situ efficient NDT method, we carried out experiments and subsequent data analysis using thermal excitation. Image processing, inverse thermal modelling and 3D numerical simulations are used and then applied to experimental data obtained in laboratory conditions.

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

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

Thanks to IFSTTAR years of experience in large scale civil engineering experiment, I4S is able to perform very long term thermal monitoring of structures exposed to environmental condition, as the solar heat flux, natural convection or seasonal perturbation. Informations system are developed to asses the data acquisition and researchers work on the quantification of the data to detect flaws emergence on structure, those techniques are also used to diagnose thermal insulation of buildings or monitoring of guided transport infrastructures, Figure 4 left. Experiments are carried out on a real transport infrastructure open to traffic and buildings. The detection of the inner structure of the deck is achieved by image processing techniques (as FFT), principal component thermography (PCT), Figure 4 right, or characterization of the inner structure thanks to an original image processing approach.

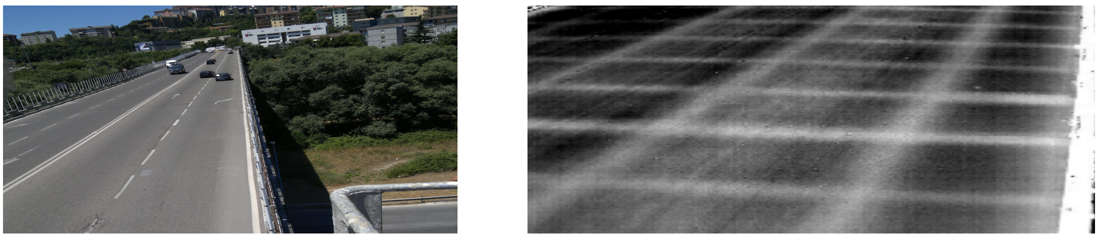

Figure 4. Left: Image in the visible spectrum of the deck surface - Right: PCT result on a bridge deck

For the next few years, I4S is actively implied in the SenseCity EQUIPEX (http://sense-city.ifsttar.fr/) where our informations systems are used to monitor a mini-city replica, Figure 5.

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

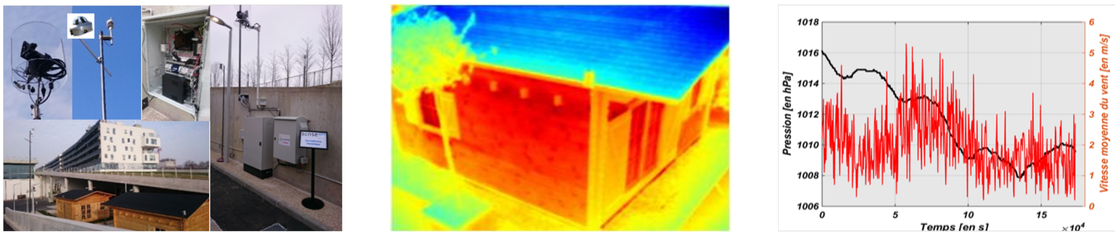

Figure 5. Various view and results of the SenseCity experimentation site - (site and hardware view, IR imaging, Environmental Monitoring)

project for IFSTTAR, which is a stakeholder in the Forever Open Road. Through its partnership with the COSYS (IFSTTAR) department, I4S is fully involved in the development of the 5th Generation Road.

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

4. Highlights of the Year

4.1. Highlights of the Year

4.1.1. Awards

- Our former PhD student Nicolas Le Touz received the Abertis Prize France for his thesis "Design and study of positive energy transport infrastructure: from thermomechanical modelling to the optimisation of such energy systems", defended in November 2018. The Abertis Prize is awarded for research in transport infrastructure management.
- Nassif Berrabah, industrial PhD student of the I4S Team in collaboration with EDF, has defended his thesis on "Inverse problems for diagnosis of electric cables from reflectometry measurements" in November 2017. The research work of his thesis received the award of Scientific Prize from EDF R&D.

5. New Software and Platforms

5.1. Platforms

5.1.1. Pegase

PEGASE is the wireless platform developed by the team. The milestones for the PEGASE platfom in 2019 are

- finalization of the PEGASE3 hardware and software platform: SDK, decoding FPGA-based GPS frames,

- capacity (demonstrated during work with CEA Lost) of synchronous transmission / reception and ultrasonic wave phase.
- Writing documentation associated with the platform (User Guide ...).
- Start of the valuation process.

A prototype for modal analysis with several PEGASE platforms was developed. To obtain detailed modal information of large and very large structures, many sensors would be required to cover the geometry of the structure with a reasonable accuracy. However, when only a limited amount of sensors is available, large structures can be measured in several sensor setups, where some sensors remain fixed and some are moved between different measurement setups. With the sensors connected to different wireless platforms, the synchronous acquisition of data is required. A solution of data acquisition synchronization, as well as signal processing for merging the information taking into account the change of sensor positions and environmental variability has been developed and presented at IWSHM [31].

6. New Results

6.1. System identification

6.1.1. On Local LTI Model Coherence for LPV Interpolation

Participant: Qinghua Zhang.

In the local approach to linear parameter varying (LPV) system identification, it is widely acknowledged that locally estimated linear state-space models should be made coherent before being interpolated, but the accurate meaning of the term " coherent " or " coherence " is rarely defined. The purpose of this study is to analyze the relevance of two existing definitions and to point out the consequence of this analysis on the practice of LPV system identification. This work has been carried out in collaboration with Lennart Ljung of Linköping University and Rik Pintelon of Vriije Universiteit Brussel, and the results have been published in [22].

6.1.2. Stability Analysis of the Kalman Predictor

Participant: Qinghua Zhang.

The stability of the Kalman filter, though less often mentioned than the optimality in the recent literature, is a crucial property for real time applications. The purpose of this paper is to complete the classical stability analysis of the Kalman filter for general time varying systems. A proof of the stability of the one step ahead predictor, which is embedded in the Kalman filter, is presented in this paper, whereas the classical results were focused on the stability of the filter. The predictor stability is particularly important for linear parameter varying (LPV) system identification by means of prediction error minimization. This work has been carried out in collaboration with Liangquan Zhang of Beijing University of Posts and Telecommunications, and the results have been published in [23].

6.1.3. Regularized Adaptive Observer to Address Deficient Excitation

Participant: Qinghua Zhang.

Adaptive observers are recursive algorithms for joint estimation of both state variables and unknown parameters. Usually some persistent excitation (PE) condition is required for the convergence of adaptive observers. However, in practice, it may happen that the PE condition is not satisfied, because the available sensor signals do not contain sufficient information for the considered recursive estimation problem, which is ill-posed. To remedy the lack of PE condition, inspired by typical methods for solving ill-posed inverse problems, this paper proposes a regularized adaptive observer for general linear time varying (LTV) systems. Regularization terms are introduced in both state and parameter estimation recursions, in order to preserve the state-parameter decoupling transformation involved in the design of the adaptive observer. Like in typical ill-posed inverse problems, regularization implies an estimation bias, which can be reduced by using prior knowledge about the unknown parameters. This work has been carried out in collaboration with Fouad Giri and Tarek Ahmed-Ali of Université de Normandie, and the results have been presented at [40].

6.2. Damage detection and localization

6.2.1. Model sensitivity clustering for damage localization

Participants: Michael Doehler, Laurent Mevel.

The purpose of this paper is the development of a working damage localization method that is applicable on real data from complex structures. To achieve this goal, robust hypothesis tests are used, the sensitivity computation of the previously published residual is revisited for more precision thanks to reduced modal truncation errors, and an adequate clustering approach is proposed for the case of a high-dimensional FE parameterization for complex structures. Finally, an application of this framework is shown for the first time on experimental data for damage localization, namely in an ambient vibration test of a 3D steel frame at the University of British Columbia. [16]

6.2.2. Robustness to temperature changes for damage localization

Participants: Laurent Mevel, Michael Doehler, Alexander Mendler.

For structures in operation, temperature has been shown to be a major nuisance to the efficiency of such methods since the modal parameters are varying not only with damage but also due to temperature variations. For detection, environmental variation is hardly taken into account in localization approaches. In this paper, we propose a sensitivity-based correction of the identified modal parameters in the damaged state with respect to the temperature field in the reference state, based on a sensitivity analysis with respect to temperature dependent parameters of the finite element model in the reference state. The approach is then applied to the Stochastic Dynamic Damage Locating Vector (SDDLV) method, where its improved performance under non-uniform temperature variations is shown in a numerical application on a beam. [18], [26]

6.2.3. Robustness to temperature changes for damage detection

Participants: Laurent Mevel, Michael Doehler, Qinghua Zhang, Eva Viefhues.

Temperature affected vibration data is evaluated with a stochastic damage detection method, which relies on a null space based residual. A new approach is proposed, using model interpolation, where a global reference model is obtained from data in the reference state at several reference temperatures. Then, for a particular testing temperature, a local reference model is derived from the global reference model. Thus, a well fitting reference null space for the formulation of the residual is available when new data is tested for damage at arbitrary temperatures. Particular attention is paid to the computation of the residual's covariance, taking into account the uncertainty related to the null space estimate. This improves the test performance, resulting in a high probability of detection (PoD) of the new interpolation approach for global and local damages compared to previous approaches. [37]

6.3. Infrared Thermography

6.3.1. Long term thermal monitoring by standard passive Infrared thermography

Participants: Thibaud Toullier, Jean Dumoulin, Laurent Mevel.

The framework of latest technological improvements in low-cost infrared cameras have brought new opportunities for long-term infrastructures monitoring. Anyway, the accurate measurement of surfaces temperatures is facing the lack of knowledge of radiatives properties of the scene. By using multi-sensors instrumentation, the measurement model can be refined to get a better estimate of the temperature. To overcome a lack of sensors instrumentation, it has been shown that online and free available climatic data can be used. [15].

6.3.2. Long term thermal monitoring by multi-spectral infrared thermography

Participants: Thibaud Toullier, Jean Dumoulin, Laurent Mevel.

Bayesian methods to estimate simultaneously the emissivity and temperature have been developed and compared to literature's methods. A radiative exchange simulator of 3D scenes have been developed to compare those different methods on numerical data. This new software uses the hardware acceleration as well as a GPGPU approach to reduce the computation time. As a consequence, obtained numerical results emphasized an advanced use of multi-spectral infrared thermography for the monitoring of structures. This simultaneous estimation enables to have an estimate of the temperature by infrared thermography with a known uncertainty. [15].

6.4. Sensor and hardware based research

6.4.1. Fiber optic and interferometry

Participants: Xavier Chapeleau, Antoine Bassil.

The assessment of Coda Wave Interferometry (CWI) and Distributed Fiber Optics Sensing (DFOS) techniques for the detection of damages in a laboratory size reinforced concrete beam is presented in this paper. The sensitivity of these two novel techniques to micro cracks is discussed and compared to standard traditional sensors. Moreover, the capacity of a DFOS technique to localize cracks and quantify crack openings is also assessed. The results show that the implementation of CWI and DFOS techniques allow the detection of early subtle changes in reinforced concrete structures until crack formation. With their ability to quantify the crack opening, following early detection and localization, DFOS techniques can achieve more effective monitoring of reinforced concrete structures. Contrary to discrete sensors, CWI and DFOS techniques cover larger areas and thus provide more efficient infrastructures asset management and maintenance operations throughout the lifetime of the structure.

6.4.2. Offset Tracking of sensor clock using Kalman filter for wireless network synchronization

Participants: David Pallier, Vincent Le Cam, Qinghua Zhang.

Wireless Sensors Networks (WSN) are more and more used in structural health monitoring applications since they represent a less expensive and non-invasive way to monitor infrastructures. Most of these applications work by merging or comparing data from several sensors located across the structure. These data often comprise measurements of physicals phenomenons evolving with time, such as acceleration and temperature. To merge or compare time-dependent data from different sensors they need to be synchronized so all the samples are time-stamped with the same time reference. An initial synchronization of the sensors is needed because sensors are independent and therefore can not be all started at the same time. Subsequent re-synchronizations are also needed since the sensors keep track of time using their imperfect local clock. This work has been presented in [34].

6.4.3. Wireless implementation of system identification techniques

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

Embedded wireless platforms such as the PEGASE platform are appealing and suitable to collect vibration data and then perform off-line and remote computation easily. To obtain detailed modal information of large and very large structures, many sensors would be required to cover the geometry of the structure with a reasonable accuracy. However, when only a limited amount of sensors is available, large structures can be measured in several sensor setups, where some sensors remain fixed and some are moved between different measurement setups. With the sensors connected to different wireless platforms, the synchronous acquisition of data is required. In this paper, a solution of data acquisition synchronization, as well as signal processing for merging the information taking into account the change of sensor positions and environmental variability is presented.

6.4.4. Management of Cloud architectures

Participants: Jean Dumoulin, Laurent Mevel.

Cloud2IR is an autonomous software architecture, allowing multi-sensor connection, dedicated to the long term thermal monitoring of infrastructures. The system has been developed in order to cut down software integration time facilitating the system adaptation to each experiment. First, a generic unit, a data management side able to aggregate any sensor data, type or size, automatically encapsulating them in various generic data format such as hierarchical data format or cloud data such as opengis standard. This whole part is also in charge of the acquisition scenario, the local storage management and the network management. Second, a specialized unit where the sensor specific development fitted to experimental requirements are addressed. The system has been deployed on two test sites for more than one year. It aggregates various sensor data issued from infrared thermal cameras, GPS units, pyranometers, weather stations. The software and some results in outdoor conditions are discussed

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

7.1.1. Collaboration with SNCF on Road circuits

Participants: Vincent Le Cam, Arthur Bouché.

The 2 objectives of the Circuit de Voie project aimed to detect the phenomenon of deshuntage are, with SNCF Innovation Research, develop criteria and models to detect, in real time, the appearance of the phenomenon, and implementing in one of several PEGASE boxes spread over several test sites these models and comparison indicators.

3 criteria have been developed and validated in simulation on real dataset: 1 criterion in residual power on the spectral band of the harmonic of rank 3, a criterion of spectral shape recognition typical in case of bad deshuntage, a statistical criterion on the RMS component of the residual signal. Future work is envisaged in 2020 to go further in comparing these models with real field data and comparison with other detection systems. Several PEGASE units have been built, deployed and implemented for one-off or long-term measurement phases, including during deshuntage tests conducted by SNCF teams.

7.1.2. Collaboration with SNCF Reseau

Participants: Vincent Le Cam, Arthur Bouché.

SNCF has commissioned 5 new DETECTEAU water level sensors adapted to the conditions of nozzles and waterways in the rail network. From a technological point of view the sensor is of small size and very weak consumption. DETECTEAU communicates according to the LORA network. From September to November 2019, one to 3 sites of LGV Paris East will probably be deployed. Scientifically a dynamic sending algorithm has been implemented, taking into account the dynamics of the watercourse (sending more information if there are phases of flood or recession). As it stands, the DETEC-TEAU project is opening the field, probably for 2020, to a more scientific follow-up of the project where the data collected will feed watershed flow models that SNCF wishes to qualify.

7.1.3. Collaboration with SNCF : Hot boxes detection

Participants: Jean Dumoulin, Thibaud Toullier.

The main strategic issue is the maintenance in operational condition of the Hot Box Detectors (DBC). The removal of the DBC from the track is part of Tech4Rail's ambition: reducing equipment to the track. The innovation aimed at in this project is to study and develop a measurement solution to be deployed at the edge of a lane out of danger zone and independent of track equipment. Among the scientific obstacles identified are the following three:

- the behavior of the measurement system in deteriorated meteorological conditions in a real site
- the design and implementation of an automated prototype for in-situ deployment (connection to an existing announcement system, hardware packaging of the system, study and design of a scalable software solution allowing pre-processing data).
- the development of automatic processing tools for the analysis of massive data generated by in-situ measurement systems

7.1.4. Contract with SIEMENS : Poof of Concept monitoring coupled with prediction model for deicing metro lane surface

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

This proof of concept aims at combining real site monitoring solutions with adjoint state FE thermal model approach to predict optimal heating required to preserve surface from icing in winter conditions. Furthermore, we introduced in our prediction model connection with in-line weather forecast provided by Meteo France Geoservice at different time horizon and spatial scale.

8. Partnerships and Cooperations

8.1. Regional Initiatives

8.1.1. SYSIFE

Participant: Ivan Guéguen.

Type: CPER + REVES project funding

Objectif: Development of a test bench for railways testing

Duration: 2019 - 2020

Coordinator : IFSTTAR

Partners: Cerema, ColasRail, Edilon, SNCF Réseau, Railenium, Vossloh

Inria contact: Ivan Guéguen

8.1.2. SHM-TGROUT

Participant: Xavier Chapeleau.

Type: Weamec regional cluster

Objectif: to assess the suitability of several non-destructive methods to detect and track the damage for metal pipes.

Duration: 2019 - 2020

Coordinator : IFSTTAR

Partners: University of Nantes, STX

Inria contact: Xavier Chapeleau

Abstract:

The cement bond between metal pipes is a very common technique in the offshore environment, particularly in the "oil and gas" sector. This technique has been used in the offshore wind sector installed to connect the structure (jacket or monopile) to its foundation. A small-scale sample of this type of cement connection was sized, and instrumented it with several technologies. sensors (including fiber optic sensors) and subjected it to axial fatigue stresses. Although the results of the instrumentation are still in operation, the damage could be detected by the various methods tested. A new trial is planned in the first half of 2020 to confirm the results obtained.

8.1.3. MUSIWIND

Participants: Xavier Chapeleau, Laurent Mevel, Frederic Gillot.

Type: RFI WIZE

Objectif: Qualify a very high precision sensor for vibratory monitoring of wind turbines, develop monitoring algorithms using SSI methods and validation indicators

Duration: 12 months in 2020

Coordinator : IFSTTAR

Partners: Inria, SERCELL, VALOREM

Inria contact: Xavier Chapeleau

Abstract: Structural health monitoring of wind turbines is becoming a real economic issue for the managers of these structures. Indeed, they are more and more demanding of new structural health control techniques that enable the implementation of an automated and planned monitoring strategy to ensure the structural integrity of their wind turbines throughout their lifetime, particularly in the case of exceptional events such as storm or earthquake. In this business sector where innovation is crucial to stay competitive, the project MusiWind aims at the hardware, software and scientific development of a new device for monitoring the structural integrity of wind turbines and their qualification in real conditions. Through a multi-sensor approach, the project integrates in particular the newQuietSeisTM low-noise accelerometer (developed by SERCEL) with a generic data acquisition card Pegase 3 (developed by IFSTTAR) on which is embedded innovative signal processing (data analysis) developed by the Ifsttar / Inria I4S joint research team. Statistical inference algorithms meant to extract structural information under ambient excitation. The originality of the project will be to develop identification methods as well as multi-varied damage indicators that merge data froms ensors of different types and qualities, as well as the fusion of complementary physical characteristics.

8.1.4. SURFEOL: SURveillance et Fiabilité des Fondations d'EOLiennes

Participants: Xavier Chapeleau, Michael Doehler, Laurent Mevel, Flavien Bouché.

The regional project SURFEOL was in collaboration with les Chantiers de l'Atlantique and ended in 2017. Many months of data were collected. Three main axes were investigated.

- Study of monitoring of off shore wind turbines
- Laboratory experiments for fatigue monitoring using fiber optic sensors
- Development of a monitoring system based on optical gages and test in real conditions on a marine buoy

A Master 2 internship was dedicated on the analysis of multiple months of data by means of data analysis and subspace identification techniques.

8.1.5. 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 objective is to correct the time drift of the quartz in wireless sensor networks. Quartz modelizations, test platforms under real GPS conditions have been built. First results are based on Kalman algorithms to correct drift[34].

8.1.6. Collaboration with GeM

Participants: Laurent Mevel, Michael Doehler.

I4S' PhD student Md Delwar Hossain Bhuyan has done his PhD on damage localization on civil structures in collaboration with GeM (Institute of Civil and Mechanical Engineering), Université de Nantes, and successfully defended in November 2017. In the follow-up, a mockup of the Saint Nazaire bridge has been funded by GeM in 2018 for damage localization, and tests on it are ongoing [25].

8.1.7. Vibration analysis by video image processing for civil engineering structure monitoring

Participants: Bian Xiong, Qinghua Zhang.

- Type: ARED (Allocations de Recherche Doctorale)
- Objective: to develop video-based methods for civil engineering structure monitoring.
- Duration: 2018 - 2021
- Coordinator : Inria
- Partners: IFSTTAR
- Inria contact: Qinghua Zhang
- Abstract:

  The I4S team develops real-time vibration analysis methods for the monitoring of civil engineering structures (bridges, buildings, etc.), usually based on mechanical sensors integrated into the monitored structures. In parallel, the team works also on image processing techniques for non-destructive testing of civil engineering construction materials. This PhD project, co-supervised with Vincent Baltazart (IFSTTAR researcher), aims to combine the two approaches in order to develop a method of vibration analysis based on image processing. Given a sequence of images of the structure to be monitored, the motion signal of the structure is derived from video image analysis, then methods of vibration analysis are applied to this motion signal. Such a solution will have the advantage of avoiding the integration of mechanical sensors into monitored structures and simplifying the maintenance of the monitoring system

8.2. National Initiatives

8.2.1. CEA List : Acoustic High Frequency synchronous and wireless

Participants: Vincent Le Cam, Arthur Bouché.

In the area of infrastructure, strengthening links with CEA-LIST and Alstom-Rail will focus on non-destructive ultrasonic testing methods for rails. We will focus in particular on the opening of cracks in the passage of the trains, which requires a very precise synchronization of the various sensors. In 2019 the first tests of validation on the site of Bar le Duc with the help of the prototype were conclusive: capacities to emit and receive ultrasonic waves in 1.4 km of rail by perfectly synchronized materials (until the microsecond UT). In 2020 the objectives of the future contract will be:

- make several boxes to carry out more complete tests
- conducting qualification test campaigns (according to CDC Alstom)
- upgrade the high frequency daughter card (with PEGASE 3 more globally)

8.2.2. 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. A smart logger and a protype have been developed and presented. A full autonomous system has been studied and developed for in-situ measurement on existing building envelope. In parallel, thermal resistance estimation method was studied. First experiments were carried out with a first generation prototype in 2019. For this purpose different instrumented building walls were built and qualified at CSTB before carrying out in-situ evaluations of the prototype.

8.3. European Initiatives

8.3.1. FP7 & H2020 Projects

8.3.1.1. 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 Marie-Sklodowska Curie Actions Innovative Training Networks)

Type of Action: MSCA-ITN-ETN

Objective: Improve energy performance of building design

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: This thesis work aims to develop and validate a method for monitoring crack openings using distributed fiber optics strain measurements. First, the various existing theories on strain transfer from the host material to the optical fiber are presented, with their validity domain. The problem of perfect interfacial bonding is then studied and a three-layer analytical model capable of handling imperfect bonding case is proposed. This model is then generalized to multi-layer systems. Experimental studies validating this new model are presented. They show that it is possible to monitor crack openings up to 1 mm with an error of less than 10% for a fiber optic cable glued on the surface. Cables embedded in concrete show less accurate results. The type of cable, the bonding length and the hardening of the concrete material also influence the accuracy of the estimated crack openings. Finally, the results of case studies on laboratory-size reinforced concrete samples are presented. They show the optical fibers capacity to detect cracks as early as ultrasonic sensors and to monitor the opening of multiple micro cracks.

8.3.1.2. DESDEMONA(DEtection of Steel Defects by Enhanced MONitoring and Automated procedure for self-inspection and maintenance)

Participants: Jean Dumoulin, Laurent Mevel, Michael Doehler, Xavier Chapeleau.

Call: H2020 -Call: RFCS-2017 (Call of the research programme of the Research Fund for Coal and Steel - 2017)

Type of Action: RFCS-RPJ (Research project)

Objective: DESDEMONA objective is the development of novel design methods, systems, procedure and technical solution, to integrate sensing and automation technologies for the purpose of self-inspection and self-monitoring of steel structures.

Duration: 36 months since 2018 June 1st

Coordinator: Pr. Vincenzo Gatulli (La Sapienza University of Rome)

Academic and industrial Partners: Sapienza Università di Roma (Italy), Universidad de Castilla – La Mancha, (Spain), Universidade do Porto (Portugal), Università di Pisa (Italy), IFSTTAR (France), Aiviewgroup srl (Italy), Sixense systems (France), Ecisa compania general de construcciones sa (Spain), Università di Cassino e del Lazio Meridionale (Italy), Universidad de Alicante (Spain), Inria (France).

Inria contact: J. Dumoulin and L. Mevel

Website: http://www.desdemonaproject.eu

Abstract: DESDEMONA objective is the development of novel design methods, systems, procedure and technical solution, to integrate sensing and automation technologies for the purpose of self-inspection and self-monitoring of steel structures. The approach will lead to an increment of the service life of existing and new steel civil and industrial infrastructure and to a decrease in the cost associated to inspections, improving human activities performed in difficult conditions, safety and workers' potential by the use of advanced tools. The research aims to expand beyond the current state-of-the-art new high-quality standard and practices for steel structure inspection and maintenance through the interrelated development of the following actions: i) steel structure geometry and condition virtualization through data fusion of image processing, thermography and vibration measurements; ii) developing a procedure for steel defect detection by robotic and automatic systems such as Unmanned Aerial Vehicles (UAV) and ground mobile robots iii) embedding sensor systems to revalorize and transform steel elements and structures into self-diagnostic (smart) elements and materials even through nanotechnologies, iv) realizing an experimental lab-based apparatus and a series of case studies inspected by intelligent and robotic systems. The project outcome will have an impact on the reduction of the cost of steel structures inspection and maintenance and on the increase of user safety and comfort in industrial and civil environment. The proposal with a multidisciplinary approach fulfils the objectives of the Strategic Research Agenda of the European Steel Technology Platform.

8.3.2. Collaborations in European Programs, Except FP7 & H2020

8.3.2.1. 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

Objective: Quantifying the value of structural health monitoring

Duration: 11/2014 - 4/2019

Coordinator: S. Thoens (DTU Denmark)

Partner: 29 countries, see https://www.cost.eu/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.

8.4. International Initiatives

8.4.1. Collaboration with University of British Columbia, Canada

Participants: Laurent Mevel, Michael Doehler, Alexander Mendler.

Alexander Mendler's PhD thesis started in September 2018 co-supervised by M. Doehler and C. Ventura. A. Mendler spent 6 months in Rennes in 2019 thanks to a MITACS grant.

8.4.2. 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 at BAM since 2016. Besides the supervision of the PhD, collaboration on temperature robustness is ongoing with BAM [18], [24].

8.4.3. Collaboration with Technical University of Denmark (DTU)

Participants: Michael Doehler, Laurent Mevel.

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, Aalborg University's PhD student Lijia Long is involved.

8.4.4. Collaboration with Aalborg University, Denmark

Participant: Michael Doehler.

Together with Structural Vibration Solutions, collaboration with Aalborg University (professor Lars Damkilde, Department of Civil Engineering) happened during the PhD of Szymon Gres on damage detection methods, with current conference publications [29], [30]. The PhD has been defended on November 19, 2019.

8.4.5. Collaboration with Laval University, Canada

Participant: Jean Dumoulin.

In the Framework of On Duty Project (http://www.ondutycanada.ca) we are working on Non Destructive Testing techniques and automation of inspection process. Jean Dumoulin spent 10 days in Canada in 2019 devoted to corrosion detection by active infrared thermography NDT approach.

8.5. International Research Visitors

8.5.1. Visits of International Scientists

Szymon Gres visited us for 2 months from January to February 2019 during his thesis.

A. Mendler got a 6 month MITACS grant to visit us from May to October 2019.

8.5.1.1. Research Stays Abroad

J. Dumoulin was with University Laval and with CNR IREA in Fall 2019.

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events selection

9.1.1.1. 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/)
- Co-organizer of sub-Program group PG4: Earth Surface Investigation Method at General Assembly of EGU 2019 (http://www.egu2019.eu/).

Q. Zhang is

- member of the international program commitee (technical associate editor) of the 21st IFAC World Congress that will take place in Berlin, Germany, July 12-17, 2020.
- member of IFAC Technical Committee on Modelling, Identification and Signal Processing (TC 1.1).
- member of IFAC Technical Committee on Adaptive and Learning Systems (TC 1.2).
- member of IFAC Technical Committee on Fault Detection, Supervision and Safety of Technical Processes (TC 6.4).

L. Mevel is

- member of the EWSHM scientific committee.

V. Le Cam is

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

M. Doehler is

- member of IFAC Technical Committee on Modelling, Identification, and Signal Processing.
- member of the IOMAC scientific committee.

9.1.1.2. Reviewers

M. Doehler was reviewer for ECC 2020.

J. Dumoulin was reviewer for EGU 2019, QIRT ASIA 2019 and SFT 2019.

Q. Zhang was reviewer for CDC 2019, IFAC Word Congress 2020.

9.1.2. Journal

9.1.2.1. 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 Executive Editor for the journal Geoscientific Instrumentation and Data Systems.

9.1.2.2. Reviewer - Reviewing Activities

L. Mevel was reviewer for Mechanical Systems and Signal Processing, Engineering Structures.Structural Control and Health Monitoring

M. Doehler was reviewer for Mechanical Systems and Signal Processing, Engineering Structures, Philosophical Transactions A Mathematical, Physical and Engineering Sciences, Computers and Structures, Structural Health Monitoring.

J. Dumoulin was reviewer for Quantitative Infrared Thermography Journal, GI Journal (EGU), SFT conference, Engineering Geology, International Journal of Pavement Research and Technology, Remote sensing of environment, Structural Health Monitoring, Composites Structures

9.1.3. Invited Talks

L. Ibos and J. Dumoulin, « Thermographie infrarouge: du laboratoire vers les mesures de terrain », Atelier Métrologie Thermique Avancée, SFT 2019 (Congrès annuel de la Société Française de Thermique), Nantes, France, 3 – 6 juin 2019.

9.1.4. Leadership within the Scientific Community

V. Le Cam organized the 2nd SHM France meeting in Nantes, together with CEA and Precend.

9.1.5. Scientific Expertise

V. Le Cam did an expertise in the context of EFFICACITY IRT. The expertise was about the instrumentation of RATP station and the control of the speed of escalators.

V. Le Cam helped SNCF Reseau to dissiminate at industrial results the monitoring of axle counters developed in 2018.

Arthur Bouché did an expertise for SNCF about electromagnetism and axle counters.

Ivan Guéguen did an expertise for ASCQUER for labelization of Lacroix Millenium lights for construction sites.

9.1.6. 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.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

J. Dumoulin

- Licence Professionnelle TAM (Techniques Avancées en Maintenance): thermographie infrarouge active, 24h, Université Paris-Est Créteil (UPEC), 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.
- With Nicolas Le Touz lecture on Solar Hybrid Roads at SMARTIE ETN Training week 2019
- Lecture on Long term thermal monitoring of Structures at SMARTIE ETN Training week 2019
- Lecture on IR for inspection and/or thermal monitoring of infrastructures: scope of application, technical solutions and analysis methods, at QIRT ASIA 2019 courses day.
- Lecture on Active Thermography for NDE at APESS 2019 (Asia-Pacific-Euro Summer School on Smart Structures).

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
- Polytech la Roche sur Yon, 8h embeded wireless algorithms §8h for David Pallier

M. Doehler

- Cycle préparatoire intégré, STPI, mathématiques, 48h TD, INSA Rennes, France

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

9.2.2. Supervision

PhD : Thibaud 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,defended on 6th November 2019. [15].

PhD : Antoine Bassil, *Fibre-optic sensor for fatigue monitoring*, D. Leduc, O. Abraham and X. Chapeleau. Ecole doctorale SPIGA, Université de Nantes, defended on 26 November 2019.

PhD : Bian Xong, *Vibration analysis by video image processing for civil engineering structure monitoring*, Q. Zhang, V. Balthazar. Ecole doctorale MathsTIC, Université de Rennes 1, since October 2018.

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

PhD : Alexander Mendler, *Vibration-based structural health monitoring of road bridges*, C. Ventura and M. Doehler. University of British Columbia, Vancouver, Canada, since September 2018.

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

Nicolas Le Touz post-doctoral project on in-situ measurement of thermal resistance of building envelopes, J. Dumoulin, December 2018- august 2019.

9.2.3. Juries

Q. Zhang participated in the following PhD defense committees:

- Missie Aguado Rojas at CentraleSupélec, on June 14, 2019.
- Tzila Ajamian at Centrale Nantes on October 24, 2019.

9.3. Popularization

9.3.1. Internal or external Inria responsibilities

L. Mevel is member of CLHSCT committee in Rennes.

L. Mevel is member of Comité de centre committee in Rennes.

L. Mevel is Head of Science in 2nd of Inria Rennes Center.

V. Le Cam is Head of SII LAb at IFSTTAR Nantes.

J. Dumoulin is scientific Head SII LAb at IFSTTAR Nantes.

9.3.2. Articles and contents

9.3.2.1. Encycopedia article on nonlinear system identification

In the second edition of Encyclopedia of Systems and Control, published by Springer in September 2019, the article on nonlinear system identification authored by Q. Zhang has been updated with the latest progresses on this topic.

Nonlinear mathematical models are essential tools in various engineering and scientific domains, where more and more data are recorded by electronic devices. How to build nonlinear mathematical models essentially based on experimental data is the topic of this entry. Due to the large extent of the topic, this entry provides only a rough overview of some well-known results, from gray-box to black-box system identification. DOI: https://doi.org/10.1007/978-1-4471-5102-9_104-2

9.3.3. Interventions

M. Doehler and Q. Zhang participated the outreach activity "J'peux pas, j'ai informatique" for school classes on April 2, 2019.

9.3.4. Creation of media or tools for science outreach

9.3.4.1. Showroom demonstrations

A damage localization mockup has been developed and installed in the showroom of Inria Rennes. It has been the support for a demonstration for the outreach activity "J'peux pas, j'ai informatique" for school classes on April 2, 2019, showing that computer science also can be related to physics and statistics. An ADT Carnot has been funded on that topic and will help the maturation of such project.

10. Bibliography

Major publications by the team in recent years

[1] J. Brouns, A. Crinière, J. Dumoulin, A. Nassiopoulos, F. Bourquin. *Diagnostic de structures de Génie Civil : Identification des propriétés spatiales et de la surface d'un défaut*, in "SFT 2014", Lyon, France, Société Française de Thermique, May 2014, https://hal.inria.fr/hal-01082184

[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

[4] J. Dumoulin, A. Crinière, R. Averty. *The detection and thermal characterization of the inner structure of the 'Musmeci' bridge deck by infrared thermography monitoring*, in "Journal of Geophysics and Engineering", December 2013, vol. 10, n^o 6, 17 p. [*DOI :* 10.1088/1742-2132/10/6/064003], https://hal.inria.fr/hal-01081320

[5] M. Döhler, L. Mevel. *Fast Multi-Order Computation of System Matrices in Subspace-Based System Identification*, in "Control Engineering Practice", September 2012, vol. 20, n^o 9, pp. 882–894

[6] M. Döhler, L. Mevel. *Modular Subspace-Based System Identification from Multi-Setup Measurements*, in "IEEE Transactions on Automatic Control", November 2012, vol. 57, n^o 11, pp. 2951–2956

[7] M. Döhler, L. Mevel. *Efficient Multi-Order Uncertainty Computation for Stochastic Subspace Identification*, in "Mechanical Systems and Signal Processing", June 2013, vol. 38, n^o 2, pp. 346–366

[8] M. Döhler, L. Mevel. *Subspace-based fault detection robust to changes in the noise covariances*, in "Automatica", September 2013, vol. 49, n^o 9, pp. 2734–2743 [*DOI :* 10.1016/j.automatica.2013.06.019], https://hal.inria.fr/hal-00907662

[9] A. Jhinaoui, L. Mevel, J. Morlier. *A new SSI algorithm for LPTV systems: application to a hinged-bladed helicopter*, in "Mechanical Systems and Signal Processing", January 2014, vol. 42, n^o 1, pp. 152–166

[10] P. LAIR, J. DUMOULIN, P. MILLAN. *Inverse method for flux characterization using infrared thermography in die forging*, in "Numerical Heat Transfer, Part A Applications", 1998, vol. 33, nº 3, pp. 267–277

[11] F. LOETE, Q. ZHANG, M. SORINE. *Experimental validation of the inverse scattering method for distributed characteristic impedance estimation*, in "IEEE Transactions on Antennas and Propagation", 2015, vol. 63, nº 6, 7 p. [*DOI :* 10.1109/TAP.2015.2417215], https://hal.inria.fr/hal-01231807

[12] L. MARIN, M. DÖHLER, D. BERNAL, L. MEVEL. *Robust statistical damage localization with stochastic load vectors*, in "Structural Control and Health Monitoring", March 2015, vol. 22, nº 3

[13] M. ZGHAL, L. MEVEL, P. DEL MORAL. *Modal parameter estimation using interacting Kalman filter*, in "Mechanical Systems and Signal Processing", August 2014, vol. 47, nº 1, pp. 139–150

[14] Q. ZHANG, M. SORINE, M. ADMANE. *Inverse Scattering for Soft Fault Diagnosis in Electric Transmission Lines*, in "IEEE Transactions on Antennas and Propagation", 2011, vol. 59, nº 1, pp. 141 - 148, https://hal.inria.fr/inria-00365991

Publications of the year

Doctoral Dissertations and Habilitation Theses

[15] T. TOULLIER. *Caractérisation conjointe de la température et des propriétés radiatives des objets par thermographie infrarouge multispectrale*, Université Rennes 1, November 2019, https://tel.archives-ouvertes.fr/tel-02389051

Articles in International Peer-Reviewed Journals

[16] S. ALLAHDADIAN, M. DÖHLER, C. VENTURA, L. MEVEL. *Towards robust statistical damage localization via model-based sensitivity clustering*, in "Mechanical Systems and Signal Processing", 2019, vol. 134, pp. 1-25 [*DOI :* 10.1016/J.YMSSP.2019.106341], https://hal.inria.fr/hal-02293021

[17] A. BASSIL, X. WANG, X. CHAPELEAU, E. NIEDERLEITHINGER, O. ABRAHAM, D. LEDUC. *Distributed fiber optics sensing and coda wave interferometry techniques for damage monitoring in concrete structures*, in "Sensors", January 2019, vol. 19, nº 2, pp. 1-15 [*DOI :* 10.3390/S19020356], https://hal.archives-ouvertes.fr/hal-02007049

[18] M. D. H. BHUYAN, G. GAUTIER, N. LE TOUZ, M. DÖHLER, F. HILLE, J. DUMOULIN, L. MEVEL. *Vibration-based damage localization with load vectors under temperature changes*, in "Structural Control and Health Monitoring", September 2019, vol. 26, nº 11, e2439 p. [*DOI :* 10.1002/STC.2439], https://hal.inria.fr/hal-02293057

[19] A. CRINIÈRE, J. DUMOULIN, L. MEVEL. *Management of local multi-sensors applied to SHM and long term infrared monitoring: Cloud2IR implementation*, in " Quantitative InfraRed Thermography Journal", March 2019, vol. 16, nº 1, pp. 55-73 [*DOI :* 10.1080/17686733.2018.1519752], https://hal.inria.fr/hal-02293809

[20] C. IBARRA-CASTANEDO, M. KLEIN, M. LAVOIE, D. PROTEAU, J. DUMOULIN. *Evaluation of Impact of Hot-Mix Asphalt Density Differentials on Thermal Streak Phenomenon by Passive Infrared Thermography*, in "Journal of Materials in Civil Engineering", October 2019, vol. 31, nº 10, 04019215 p. [*DOI :* 10.1061/(ASCE)MT.1943-5533.0002822], https://hal.inria.fr/hal-02294005

[21] Y. YANG, T. V. WU, A. SEMPEY, J. DUMOULIN, J. C. BATSALE. *Short time non-destructive evaluation of thermal performances of building walls by studying transient heat transfer*, in "Energy and Buildings", February 2019, vol. 184, pp. 141-151 [*DOI :* 10.1016/J.ENBUILD.2018.12.002], https://hal.archives-ouvertes.fr/hal-02044900

[22] Q. ZHANG, L. LJUNG, R. PINTELON. *On Local LTI Model Coherence for LPV Interpolation*, in "IEEE Transactions on Automatic Control", October 2019, 6 p. [*DOI :* 10.1109/TAC.2019.2948898], https://hal.inria.fr/hal-01758337

[23] Q. ZHANG, L. ZHANG. *Stability Analysis of the Kalman Predictor*, in "International Journal of Control", July 2019, pp. 1-16 [*DOI :* 10.1080/00207179.2019.1638971], https://hal.inria.fr/hal-02373906

Invited Conferences

[24] M. BAESSLER, M. D. H. BHUYAN, F. HILLE, E. VIEFHUES, M. DÖHLER, L. MEVEL. *Impact of environmental based effects on SHM strategies*, in "SEMC 2019 - 7th International Conference on Structural Engineering, Mechanics and Computation", Cape Town, South Africa, September 2019, pp. 1-6, https://hal.inria.fr/hal-02290909

International Conferences with Proceedings

[25] M. D. H. BHUYAN, M. DÖHLER, Y. LECIEUX, C. LUPI, J.-C. THOMAS, F. SCHOEFS, F. HILLE, L. MEVEL. *Statistical subspace based damage localization on Saint-Nazaire Bridge mock-up*, in "IOMAC 2019 - 8th International Operational Modal Analysis Conference", Copenhagen, Denmark, May 2019, pp. 1-9, https://hal.inria.fr/hal-02143530

[26] M. D. H. BHUYAN, N. LE TOUZ, G. GAUTIER, M. DÖHLER, F. HILLE, J. DUMOULIN, L. MEVEL. *Load vector based damage localization with rejection of the temperature effect*, in "IOMAC 2019 - 8th International Operational Modal Analysis Conference", Copenhagen, Denmark, May 2019, pp. 1-10, https://hal.inria.fr/hal-02143742

[27] J. DUMOULIN. *Uncooled infrared thermal camera for thermal monitoring or Non-Destructive Testing of Civil Engineering structures*, in "ANCRiSST 2019 - 14th International Workshop on Advanced Smart Materials and Smart Structures Technology", Rome, Italy, July 2019, https://hal.inria.fr/hal-02294079

[28] L. GAVÉRINA, T. HA, J. WAEYTENS, V. FEUILLET, J.-L. MANCEAU, L. PFEIFFER, J.-P. MONCHEAU, M. MARCHETTI, L. IBOS, J. DUMOULIN. *Study and designed of an active infrared system for in-situ characterization of thermal resistance of building envelopes*, in "QIRT ASIA 2019 - 3rd Asian Conference on Quantitative InfraRed Thermography", Tokyo, Japan, July 2019, https://hal.inria.fr/hal-02294671

[29] S. GRES, M. DÖHLER, P. ANDERSEN, L. DAMKILDE, L. MEVEL. *Hankel matrix normalization for robust damage detection*, in "IOMAC 2019 - 8th International Operational Modal Analysis Conference", Copenhagen, Denmark, May 2019, pp. 1-8, https://hal.inria.fr/hal-02143749

[30] S. GRES, M. DÖHLER, P. ANDERSEN, L. MEVEL. *Variance computation of MAC and MPC for real-valued mode shapes from the stabilization diagram*, in "IOMAC 2019 - 8th International Operational Modal Analysis Conference", Copenhagen, Denmark, May 2019, pp. 1-9, https://hal.inria.fr/hal-02143765

[31] M. LE PEN, A. BOUCHÉ, I. GUÉGUEN, M. DÖHLER, L. MEVEL, V. LE CAM. *Phased and synchronous sampling between multiple smart network sensors for modal assessment of large structures*, in "IWSHM 2019

- 12th International Workshop on Structural Health Monitoring", Stanford, CA, United States, September 2019, pp. 1-9, https://hal.inria.fr/hal-02290901

[32] N. LE TOUZ, J. DUMOULIN. *Study of an optimal command law combining weather forecast and energy reduction for transport structure surface de-icing by Joule effect*, in "ANCRiSST 2019 - 14th International Workshop on Advanced Smart Materials and Smart Structures Technology", Rome, Italy, July 2019, https://hal.inria.fr/hal-02294081

[33] A. MENDLER, S. ALLAHDADIAN, M. DÖHLER, L. MEVEL, C. VENTURA. *Minimum detectable damage for stochastic subspace-based methods*, in "IOMAC 2019 - 8th International Operational Modal Analysis Conference", Copenhagen, Denmark, May 2019, pp. 1-11, https://hal.inria.fr/hal-02142994

[34] D. PALLIER, V. LE CAM, A. BOUCHE, S. PILLEMENT, Q. ZHANG, L. MEVEL. *Offset Tracking of sensor clock using Kalman filter for wireless network synchronization*, in "IWSHM 2019 - 12th International Workshop on Structural Health Monitoring", Stanford, California, United States, IWSHM 2019, September 2019, paper #516 p. , https://hal.archives-ouvertes.fr/hal-02155889

[35] A. RUAS, F. BOURQUIN, J. DUMOULIN, B. LEBENTAL. *Sense-City innovation lab supporting recent advances on Monitoring of urban operations*, in "EGU 2019 - European Geoscience Union", Vienne, Austria, April 2019, https://hal.inria.fr/hal-02294567

[36] T. TOULLIER, J. DUMOULIN, L. MEVEL. *Study of complementary multi-sensors data influence on infrared thermography measurements for in-situ long-term monitoring*, in "2019 - Multimodal Sensing and Artificial Intelligence: Technologies and Applications", Munich, Germany, SPIE, June 2019, vol. 11059, pp. 1-10 [*DOI :* 10.1117/12.2526229], https://hal.archives-ouvertes.fr/hal-02264743

[37] E. VIEFHUES, M. DÖHLER, Q. ZHANG, F. HILLE, L. MEVEL. *Subspace-based damage detection with rejection of the temperature effect and uncertainty in the reference*, in "IOMAC 2019 - 8th International Operational Modal Analysis Conference", Copenhagen, Denmark, May 2019, pp. 1-11, https://hal.inria.fr/hal-02143745

Conferences without Proceedings

[38] T. TOULLIER, J. DUMOULIN, V. BOURGEOIS. *Comparative study of moving train hot boxes pre-detection and axles counting by in-situ implementation of two infrared cameras*, in "QIRT ASIA 2019 - Quantitative InfraRed Thermography Conference", Tokyo, Japan, July 2019, https://hal.archives-ouvertes.fr/hal-02264672

[39] T. TOULLIER, J. DUMOULIN, L. MEVEL. *Étude et développement d'un simulateur d'échanges radiatifs dans des scènes 3D statiques et dynamiques surveillées par thermographie infrarouge*, in "SFT 2019 - 27eme congrès français de thermique", Nantes, France, June 2019, pp. 1-8, https://hal.archives-ouvertes.fr/hal-02264749

[40] Q. ZHANG, F. GIRI, T. AHMED-ALI. *Regularized Adaptive Observer to Address Deficient Excitation*, in "13th IFAC Workshop on Adaptive and Learning Control Systems (ALCOS 2019)", Winchester, United Kingdom, December 2019, https://hal.archives-ouvertes.fr/hal-02414207

Other Publications

[41] J. Dumoulin, L. Gavérina, C. Ibarra-Castanedo, M. Klein, X. Maldague. *Non Destructive Testing of CFRP by active infrared thermography using uncooled IRFPA camera mounted on mobile system*, April 2019, EGU 2019 - European Geoscience Union, Poster, https://hal.inria.fr/hal-02294153

[42] M. Ribaud, C. Blanchet-Scalliet, F. Gillot, C. Helbert. *Robustness kriging-based optimization*, February 2019, working paper or preprint, https://hal.archives-ouvertes.fr/hal-01829889

[43] T. Toullier, J. Dumoulin, L. Mevel. *Sensitivity of different methods for simultaneous evaluation of emissivity and temperature through multispectral infrared thermography simulation*, April 2019, vol. 21, 1 p. , EGU 2019 - European Geoscience Union, Poster, https://hal.archives-ouvertes.fr/hal-02264677

References in notes

[44] M. Basseville, I. V. Nikiforov. *Fault isolation for diagnosis : nuisance rejection and multiple hypotheses testing*, in "Annual Reviews in Control", December 2002, vol. 26, n^o 2, pp. 189–202, http://dx.doi.org/10.1016/S1367-5788(02)00029-9

[45] B. Delyon, A. Juditsky, A. Benveniste. *On the relationship between identification and local tests*, IRISA, May 1997, n^o 1104, ftp://ftp.irisa.fr/techreports/1997/PI-1104.ps.gz

[46] M. Jaulent. *The inverse scattering problem for LCRG transmission lines*, in "Journal of Mathematical Physics", December 1982, vol. 23, n^o 12, pp. 2286-2290

[47] G. L. Lamb. *Elements of Soliton Theory*, John Wiley & Sons, New York, 1980

[48] M. Oumri. *Fault diagnosis of wired electric networks by reflectometry*, Université Paris Sud - Paris XI, May 2014, https://tel.archives-ouvertes.fr/tel-01165039

[49] C. R. Paul. *Analysis of multiconductor transmission lines*, Wiley, New York, 2008

[50] H. Tang, Q. Zhang. *An Inverse Scattering Approach to Soft Fault Diagnosis in Lossy Electric Transmission Lines*, in "IEEE Trans. on Antennas and Propagation", 2011, vol. 59, n^o 10, pp. 3730-3737, http://dx.doi.org/10.1109/TAP.2011.2163772

[51] P. Van Overschee, B. de Moor. *Subspace Identification for Linear Systems*, Kluwer Academic Publishers, Boston, 1996

[52] F. Visco Comandini. *Some inverse scattering problems on star-shaped graphs: application to fault detection on electrical transmission line networks*, Université de Versailles-Saint Quentin en Yvelines, December 2011, https://tel.archives-ouvertes.fr/tel-00748216