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

Activity Report 2018

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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Project-Team I4S

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A6.2.1. - Numerical analysis of PDE and ODE
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A6.2.6. - Optimization
A6.3.1. - Inverse problems
A6.3.3. - Data processing
A6.3.4. - Model reduction
A6.3.5. - Uncertainty Quantification
A6.4.3. - Observability and Controlability

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

1. Team, Visitors, External Collaborators

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2. Overall Objectives

2.1. Overall Objectives

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

2.1.1. In Summary

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

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

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

2.1.1.1. Objectives

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

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

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

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

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

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

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

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

2.1.2.1. *Multi-fold thermal effects*

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

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

2.1.2.2. *Toward a multidisciplinary approach*

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

Temperature rejection is the primary focus and 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 [57].

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

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

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

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

where:

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

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

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

3.1.2. Detection

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

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

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

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

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

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

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

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

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

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

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

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

3.1.2.1. Residual associated with subspace identification.

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

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

and to define the residual vector:

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

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

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

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

The central limit theorem shows [51] 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 :

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

where

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

3.1.3. Diagnostics

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

The question: *which (subsets of) components of θ have changed ?*, can be addressed using either nuisance parameters elimination methods or a multiple hypotheses testing approach [50].

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 :

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

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

3.2. Thermal methods

3.2.1. Infrared thermography and heat transfer

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

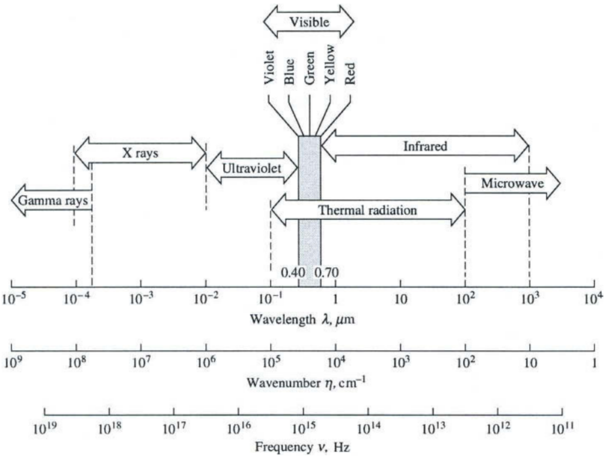

Figure 1. Electromagnetic spectrum - Credit MODEST, M.F. (1993). Radiative Heat Transfer. Academic Press.

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

Our work is concentrated in the mid infrared spectral band. Keep in mind that Table 1 represents the ISO 20473 division scheme, in the literature boundaries between bands can move slightly.

The Plank's law, proposed by Max Planck 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:

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

with

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

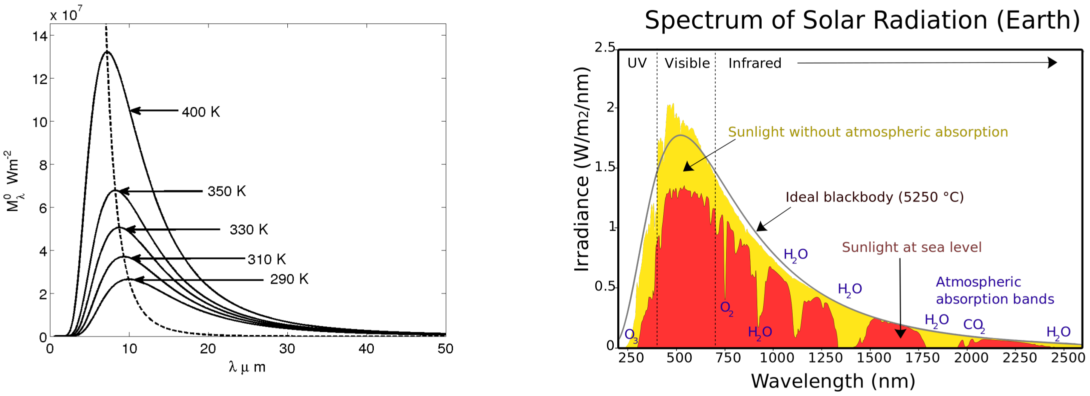

Figure 2. Left: Plank's law at various temperatures - Right: Energy spectrum of the atmosphere

By generalizing the Plank's law with the Stefan Boltzmann law (proposed first in 1879 and then in 1884 by Joseph Stefan and Ludwig Boltzmann), it is possible to address mathematically the energy spectrum of real body at each wavelength 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], [56]. 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 [58], [54]. 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.

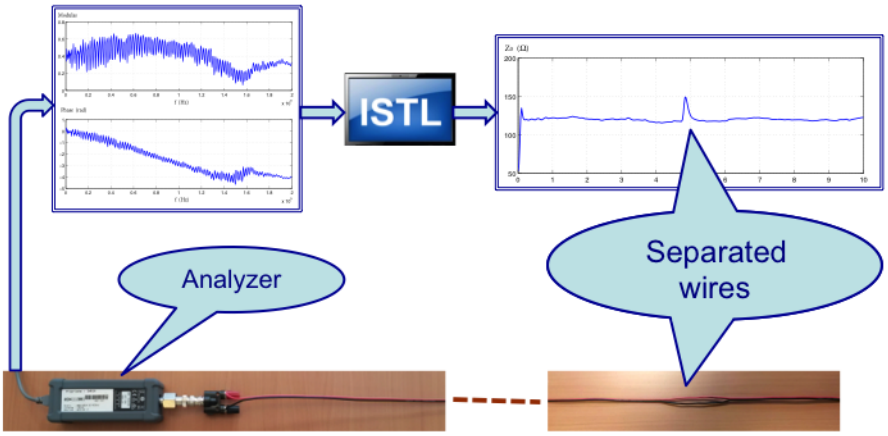

Figure 3. Inverse scattering software (ISTL) for cable soft fault diagnosis.

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 [55]

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

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

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

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

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

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

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

3.3.2. The inverse scattering theory applied to cables

The inverse scattering transform was developed during the 1970s-1980s for the analysis of some nonlinear partial differential equations [53]. The visionary idea of applying this theory to solving the cable inverse problem goes also back to the 1980s [52]. After having completed some theoretic results directly linked to practice [14], [56], 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.

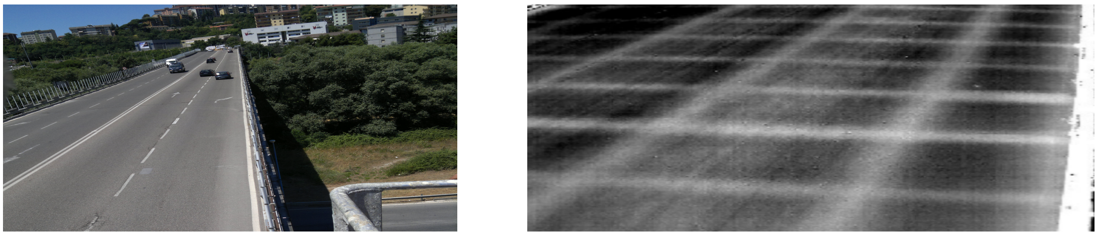

Figure 4. Left: Image in the visible spectrum of the deck surface - Right: PCT result on a bridge deck

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

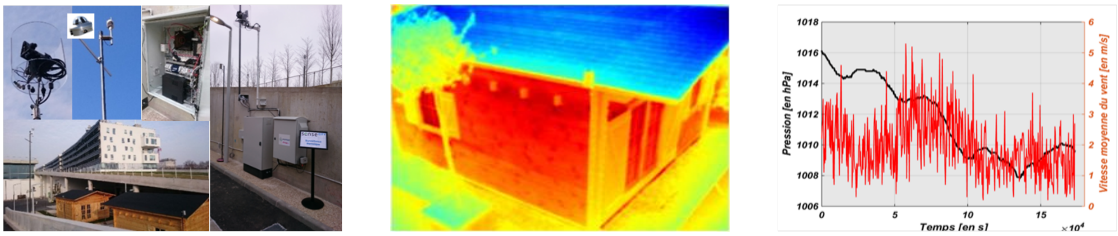

Figure 5. Various view and results of the SenseCity experimentation site - (site and hardware view, IR imaging, Environmental Monitoring)

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

BEST PAPER AWARD:

[30]
X. LORANG, S. KERBAL, L. LEMARCHAND, V. LE CAM, J.-J. MOGORO. *New detection criteria and shunting monitoring in railway track circuit receivers*, in "IWSHM-RS 2018 - 2nd International Workshop on Structural Health Monitoring for Railway Systems", Qingdao, China, October 2018, pp. 1-10, https://hal.inria.fr/hal-01898678

5. New Results

5.1. System identification

5.1.1. Linear parameter varying system local model interpolation

Participant: Qinghua Zhang.

The local approach to linear parameter varying (LPV) system identification consists in interpolating a collection of linear time invariant (LTI) models, which have been estimated from data acquired at different working points of a nonlinear system. Interpolation is essential in this approach. When the local LTI models are in state-space form, as each local model can be estimated with an arbitrary state basis, it is widely acknowledged that the local models should be made coherent before their interpolation. In order to avoid the delicate task of making local state-space models coherent, a new interpolation method of local state-space models is proposed in this work, which does not require coherent local models. This method is based on the reduction of the large state-space model built by combining the local models. This work has been presented at SYSID 2018 [39].

5.1.2. State estimation for stochastic time varying systems with disturbance rejection

Participant: Qinghua Zhang.

State estimation in the presence of unknown disturbances is useful for the design of robust systems in different engineering fields. Most results available on this topic are restricted to linear time invariant (LTI) systems, whereas linear time varying (LTV) systems have been studied to a lesser extent. Existing results on LTV systems are mainly based on the minimization of the state estimation error covariance, ignoring the important issue of the stability of the state estimation error dynamics, which has been a main focus of the studies in the LTI case. The purpose of this work is to propose a numerically efficient algorithm for state estimation with disturbance rejection, in the general framework of LTV stochastic systems, including linear parameter varying (LPV) systems, with easily checkable conditions guaranteeing the stability of the algorithm. The design method is conceptually simple: disturbance is first rejected from the state equation by appropriate output injection, then the Kalman filter is applied to the resulting state-space model after the output injection. This work has been carried out in collaboration with Beijing University of Posts and Telecommunications (China) and has been presented at SYSID 2018 [40].

5.1.3. Variance estimation of modal indicators from subspace-based system identification

Participants: Michael Doehler, Laurent Mevel.

This work has been carried out in collaboration with Szymon Gres at Aalborg University and Palle Andersen at SVS.

One of the other practical modal indicators is Modal Assurance Criterion (MAC), for which uncertainty computation scheme is missing. This paper builds on the previous results using the propagation of the measurement uncertainties to estimates of MAC. The sensitivity of the MAC with respect to output covariances is derived using a first order perturbations and the uncertainties are propagated using the Delta method. The influence of the underlying mode shape scaling on both the uncertainty of mode shapes and MAC is investigated [22].

5.1.4. On damage detection system information for structural systems

5.1.4.1. On damage detection system information for structural systems

Participant: Michael Doehler.

Damage detection systems (DDSs) provide information on the integrity of structural systems in contrast to local information from inspections or non-destructive testing (NDT) techniques. In this paper, an approach is developed that utilizes DDS information to update structural system reliability and integrate this information into risk and decision analyses. For updating of the structural system reliability, an approach is developed based on Bayesian updating facilitating the use of DDS information on structural system level and thus for a structural system risk analysis. The structural system risk analysis encompasses the static, dynamic, deterioration, reliability and consequence models, which provide the basis for calculating the direct risks due to component failure and the indirect risks due to system failure[16].

5.1.4.2. The effects of deterioration models on the value of damage detection information

Participant: Michael Doehler.

This paper addresses the effects of the deterioration on the value of damage detection information. The quantification of the value of damage detection information for deteriorated structures is based on Bayesian pre-posterior decision analysis, comprising structural system performance models, consequence, benefit and costs models and damage detection information models throughout the service life of a structural system. With the developed approach, the value of damage detection information for a statically determinate Pratt truss bridge girder subjected to different deterioration models is calculated. The analysis shows the impact of the deterioration model parameters on the value of damage detection information. [28].

5.1.4.3. The effects of SHM system parameters on the value of damage detection information

Participant: Michael Doehler.

This paper addresses how the value of damage detection information depends on key parameters of the Structural Health Monitoring (SHM) system including number of sensors and sensor locations. The quantification of the value of information (VoI) is an expected utility based Bayesian decision analysis method for quantifying the difference of the expected economic benefits with and without information. The (pre-)posterior probability is computed utilizing the Bayesian updating theorem for all possible indications. Through the analysis of the value of information with different SHM system characteristics, the settings of DDS can be optimized for minimum expected costs and risks before implementation [29].

5.1.5. Filtering approaches for damage detection

5.1.5.1. Adaptive Kalman filter for actuator fault diagnosis

Participant: Qinghua Zhang.

An adaptive Kalman filter is proposed in this work for actuator fault diagnosis in discrete time stochastic time varying systems. By modeling actuator faults as parameter changes, fault diagnosis is performed through joint state-parameter estimation in the considered stochastic framework. Under the classical uniform complete observability-controllability conditions and a persistent excitation condition, the exponential stability of the proposed adaptive Kalman filter is rigorously analyzed. In addition to the minimum variance property of the combined state and parameter estimation errors, it is shown that the parameter estimation within the proposed adaptive Kalman filter is equivalent to the recursive least squares algorithm formulated for a fictive regression problem. These results have been published in [17].

5.1.5.2. Zonotopic state estimation and fault detection for systems with both time-varing and time-invariant uncertainties

Participant: Qinghua Zhang.

This paper proposes a robust guaranteed state estimation method with application to fault detection by combining H_∞ observer design with zonotopic analysis for discrete-time systems with both time-varing and time-invariant uncertainties. In order to improve the estimation accuracy, based on the H_∞ technique, the observer design is achieved by solving a linear matrix inequality. The main contribution of this paper lies in that the time invariance of some uncertainties is considered to reduce the conservatism of interval estimation. This work has been carried out in collaboration with Harbin Institute of Technology (China) and with Universitat Politècnica de Catalunya (Spain), and has been presented at SAFEPROCESS 2018 [37].

5.1.5.3. Local adaptive observers for time-varying systems with parameter-dependent state matrices

Participant: Qinghua Zhang.

The purpose of this work is to design an adaptive observer for linear time-varying systems whose state matrix is affine in some unknown parameters. In this case, the proposed observer generates state and parameter estimates, which exponentially converge to the plant state and the true parameters, respectively. The results are then extended to systems whose state matrix is nonlinear, instead of being affine, in the unknown parameters. This work has been carried out in collaboration with Université de Lorraine-CNRS-CRAN and has been presented at CDC 2018 [45].

5.1.5.4. Seismic-induced damage detection through parallel force and parameter estimation using an improved interacting Particle-Kalman filter

Standard filtering techniques for structural parameter estimation assume that the input force is either known or can be replicated using a known white Gaussian model. Unfortunately for structures subjected to seismic excitation, the input time history is unknown and also no previously known representative model is available. In this paper, the input force is considered to be an additional state that is estimated in parallel to the structural parameters. Two concurrent filters are employed for parameters and force respectively. For the parameters, an interacting Particle-Kalman filter is used to target systems with correlated noise. Alongside this, a second filter is used to estimate the seismic force acting on the structure [15].

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

Participants: Antoine Crinière, Laurent Mevel, Jean Dumoulin.

Existing filtering based structural health monitoring (SHM) algorithms assume constant noise environment which does not always conform to the reality as noise is hardly stationary. Thus to ensure optimal solution even with non-stationary noise processes, the assumed statistical noise models have to be updated periodically. This work incorporates a modification in the existing Interacting Particle-Kalman Filter (IPKF) to enhance its detection capability in presence of non-stationary noise processes. The Kalman filters (KF) within the IPKF have been replaced with a maximum Correntropy criterion (MCC) based KF that, unlike regular KF, takes moments beyond second order into consideration [32].

5.1.6. Damage localization for mechanical structures

5.1.6.1. Damage localization using the stochastic load vectors

Participants: Laurent Mevel, Michael Doehler.

This work was done in collaboration with BAM (Berlin) and GEM (Nantes).

In this work, a benchmark application is proposed, namely a 1/200 scale model of the Saint-Nazaire Bridge, which is a cable-stayed bridge spanning the Loire River near the river's mouth. The region of interest, the central metallic structure, measures 720 meters. The aim of the instrumentation is to assess the capability of damage assessment methods to assess a cable failure. The model is instrumented with ten accelerometers and excited by white noise. A damage localization method is applied to test the proposed setup, namely the statistical damage locating vector approach (S-SDDLV). With this method, vibration measurements from the (healthy) reference and damaged states of the structure are confronted to a finite element of the reference state. Damage indicators are provided for the different structural elements that are easy to compute, without updating the model parameters, and taking into account the intrinsic uncertainty of noisy measurements. [21].

5.1.6.2. Asymptotic analysis of subspace-based data-driven residual for fault detection with uncertain reference

Participants: Laurent Mevel, Michael Doehler, Eva Viefhues.

This work was in collaboration with BAM (Berlin).

The local asymptotic approach is promising for vibration-based fault diagnosis when associated to a subspace-based residual function and efficient hypothesis testing tools. In the residual function, the left null space of the observability matrix associated to a reference model is confronted to the Hankel matrix of output covariances estimated from test data. When this left null space is not perfectly known from a model, it should be replaced by an estimate from data to avoid model errors in the residual computation. In this paper, the asymptotic distribution of the resulting data-driven residual is analyzed and its covariance is estimated, which includes also the covariance related to the reference null space estimate [36].

5.1.7. Smarts roads and R5G

5.1.7.1. Multi-physics models for Energy Harvesting performance evaluation

Participants: Jean Dumoulin, Nicolas Le Touz.

We present in this paper the concept of solar hybrid road and focus on the thermal performances of such system. A finite element model is presented to couple thermal diffusion, hydraulic convection and radiative transfer. This numerical model allows to compute the temperature field for different weather conditions and also to evaluate the thermal performances of the system. Annual simulations are performed and a comparison between two surface layer solutions for different locations and climates is presented and discussed[23].

5.1.7.2. *Optimal command for defreezing of solar road*

Participants: Jean Dumoulin, Nicolas Le Touz.

The study presented in [26] aims to optimize the amount of energy to bring to a hybrid solar road to prevent the formation of ice on the surface. The optimal control law studied is based on a finite element multiphysics model, developed to compute the temperature field in the structure under varying environmental conditions presented in [25]. A penalization of freezing periods at the surface is introduced and the energy to be supplied to the system to preserve it is calculated from the adjoint state method [24].

5.1.8. *Infrared Thermography*

5.1.8.1. *Sensitivity of infrared camera to environmental parameters*

Participants: Laurent Mevel, Jean Dumoulin, Thibaud Toullier.

The purpose of this study is to characterize the influence of environmental parameters for long-term in-situ structure monitoring as well as projections errors due to camera view and digitization. The model used to convert 3 year gathered data to temperature is firstly presented and discussed. Then, the effect of camera resectioning on infrared measurements is commented. Finally, the effect of the environmental parameters is studied and perspectives are proposed [35].

5.1.8.2. *Joint Estimation of emissivity and temeperature*

Participants: Laurent Mevel, Jean Dumoulin, Thibaud Toullier.

This study deals with the simultaneous assessment of emissivity and surface temperature. of objects observed by in-situ infrared thermography. Temperature measurement by thermography infrared is hampered by the lack of knowledge of the radiative properties of the real world. The light received from a target by an infrared camera is estimated by the method of progressive radiosities implemented on a map graphic in order evaluate the sensitivity of four methods of separation of emissivity and temperature [34].

5.1.9. *Sensor and hardware based research*

5.1.9.1. *Reflectometry*

Participant: Qinghua Zhang.

5.1.9.2. *De-embedding unmatched connectors for electric cable fault diagnosis*

Participant: Qinghua Zhang.

In order to make accurate reflectometry measurements on electric cables for fault diagnosis, connector de-embedding is a procedure for compensating measurement distortions caused by unmatched connectors. The key step in such a procedure is the characterization of the connectors, which is realized through measurements on a pair of connectors linked by a short cable segment. The analysis for deducing the characteristics of a single connector from measurements made on an assembled pair is known as the bisection problem. In this paper, after recalling the underdetermined nature of the bisection problem, a practically effective de-embedding procedure is proposed based on a particular regularization technique. This work has been carried out in collaboration with EDF R&D and has been presented at SAFEPROCESS 2018 [38].

5.1.9.3. *Active Infrared thermography by robot*

Participants: Jean Dumoulin, Ludovic Gaverina.

In this paper, two Non Destructive Testing approaches by active infrared thermography mounted on a 6-axis robot are presented and studied. An automated procedure is proposed to reconstruct thermal image sequences issued from the two scanning procedure studied: Line Scan and Flying Line procedures. Defective area detection is performed by image processing and an inverse technique based on thermal quadrupole method is used to map the depth of flaws [31].

5.1.9.4. Shunting monitoring in railway track circuit receivers

Participant: Vincent Le Cam.

Track circuits play a major role in railway signaling. In some exceptional conditions, poor rail/wheel contact conditions may lead to a non-detection of the train on the zone. The paper presents new detection approaches based on signal processing on an experiment with a dedicated train running on a track equipped with a track circuit. The second objective is to present a strategy to test new detection criteria on commercial zones over a long period of time using PEGASE [30].

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

6.1.1. Contract with SNCF: DEMETER

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

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

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

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

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

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

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

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

For the future, new projects related to

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

have been initiated with SNCF R&D department.

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

Participants: Vincent Le Cam, Mathieu Le Pen.

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

Following a 2016 contract, a new contract was signed in 2017 until end 2018, with the company SDEL-CC, a 100% affiliate of the VINCI Group, Energy department. The project exploits the unique time stamp capacity of the PEGASE 2 platform up to 50 nanoseconds, independently of distances in the network of PEGASE2 nodes. The synchronization capacity is employed to design a sensor prototype based on PEGASE 2 to time-stamp the current wave after a lightning impact on a high-voltage line. By knowing the exact time, the wave can be seen at each extremity of the electrical line to localize accurately the lightning impact point.

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

Discussions are ongoing with SDEL-CC to transform the prototype into a future product.

7. Partnerships and Cooperations

7.1. Regional Initiatives

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

Participants: Jean Dumoulin, Antoine Crinière, Frederic Gillot.

Type: Labex COMINLABS

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

Duration: Since November 2016 to Nov. 2019.

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

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

Inria contact: Jean Dumoulin

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

Algorithms for two emerging applications of this problem will be developed: Free-viewpoint Television (FTV) and massive requests to a database collecting data from a large-scale sensor network (such as Smart Cities) in which I4S is involved. Compression of spatio-temporally correlated and massive georeferenced Data have been investigated [42].

7.1.2. MAG2C-Pont Tabarly

Participants: Ivan Guéguen, Jean Dumoulin.

Type: GIS

Objectif: bridge instrumentation

Duration: Since 2014

Coordinator: LIRGEC

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

Inria contact: Ivan Guéguen

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

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

Participants: Xavier Chapeleau, Ivan Guéguen.

Type: GIS

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

Duration: Since 2015

Coordinator : LIRGEC

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

Inria contact: Xavier Chapeleau

Abstract: The project deals with the instrumentation of an onshore WIND turbine's slab foundation and tower. The aim is to experiment sensors and methods for structural integrity monitoring of an onshore wind turbine under real conditions and to qualify them over long term. Fiber optic sensors were installed in the slab foundation before casting and accelerometers were placed at several level in the tower of the wind turbine. Since July 2017, data from accelerometers were logged on a web data server.

7.1.4. Collaboration with GeM

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

Md Delwar Hossain Bhuyan has done his PhD on damage localisation on civil structures in collaboration with GeM (Institute of Civil and Mechanical Engineering), Université de Nantes. The thesis is co-directed by L. Mevel, and F. Schoefs from GeM, with supervision shared with M. Doehler and Y. Lecieux from GeM. It is funded by the Brittany region for 3 years and has been successfully defended in November 2017. In 2018, a mockup of the Saint Nazaire bridge has been funded by GAM and tested for damage localization.

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

7.2. National Initiatives

7.2.1. 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 [31]. A smart logger and a protype have been developed and presented [44].

7.3. European Initiatives

7.3.1. FP7 & H2020 Projects

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

A state of the Art about distributed optical fiber sensor's technology for crack detection in concrete was done together with experimental tests to assess linear models. More precisely, three points bending tests were performed on reinforced concrete beams instrumented with fiber optic cables embedded and attached to the concrete surface. The analytical expressions of linear models were fitted to strain measurements to deduce the cracks opening during the test. The comparison of these results with those obtained with traditional extensometers placed around the cracks showed a good agreement for crack openings reaching 150νm in single crack case. This model was also validated in multiple neighboring crack case until 400νm. In order to focus more on the sensor/host material system properties, wedge-splitting tests made it possible to attend higher crack openings for a single crack case allowing us to better analyze the transition from elastic to post elastic behavior of the optical cable. The use of different types of cables with relatively different mechanical properties will allow us in the near future to choose the best cable configuration for monitoring of concrete structures.

7.3.1.2. 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.

7.3.2. Collaborations in European Programs, Except FP7 & H2020

7.3.2.1. 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.

7.3.2.2. PROCOPE 37826QE

Participants: Michael Doehler, Laurent Mevel, Eva Viefhues, Frederic Gillot.

Type: PHC PROCOPE

Objective: Statistical damage localization for civil structures

Duration: 01/2017 - 12/2018

Coordinator: M. Doehler

Partner: BAM German Federal Institute for Materials Research and Testing

Inria contact: M. Doehler

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

7.3.2.3. Innobooster

Participants: Michael Doehler, Laurent Mevel.

Type: Danish Innovation Fund

Objective: Methods for mode shape uncertainty quantification

Duration: 2017 - 2018

Coordinator: M. Doehler

Partner: Structural Vibration Solutions A/S, Denmark

Inria contact: M. Doehler

Abstract: With this grant for industrial research and transfer, methods for uncertainty quantification of mode shapes are developed with the objective of producing a prototype for transfer to SVS' ARTeMIS software.

7.4. International Initiatives

7.4.1. 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.

7.4.2. 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 of the BAM institut since 2016.

7.4.3. Collaboration with Technical University of Denmark (DTU)

Participant: Michael Doehler.

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

7.4.4. Collaboration with Aalborg University, Denmark

Participant: Michael Doehler.

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

7.4.5. 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.

7.5. International Research Visitors

Szymon Gres visited us for 3 months from April to June 2018 during his thesis.

7.5.1. Visits to International Teams

7.5.1.1. Research Stays Abroad

During INFRASTAR project, Antoine Bassil

- visited BAM (3 months in 2017) on the assesment the relevant of coupling fIber optics and CODA waves techniques to crack monitoring
- visited EPFL (3 months in 2018) on the issue of long term monitoring of a special material like Ultra High Performance Reinforced Concrete (UHPFRC) using a distributed fiber optic system.

8. Dissemination

8.1. Promoting Scientific Activities

8.1.1. Scientific Events Organisation

8.1.1.1. Member of the Conference Program Committees

J.Dumoulin is

- member of the scientific committee of the GI Division (Geosciences Instrumentation and Data Systems) of EGU (European Geosciences Union) for infrastructure instrumentation and monitoring since April 2013. (http://www.egu.eu/gi/structure/)
- member of the scientific committee of QIRT (quantitative Infrared Thermography) since February 2014 (http://www.qirt.org/)
- organizer and co-chair of a session at EGU 2018 (http://www.egu2018.eu/).

Q. Zhang is

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

L. Mevel is

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

V. Le Cam is

- member of the IWSHM scientific committee.
- head and general secretary of the EWSHM scientific committee.
- session chairman for EWSHM 2018 in Manchester, UK.

M. Doehler is

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

8.1.1.2. Reviewer

Q. Zhang was reviewer for CDC 2018, ACC 2019.

M. Doehler was reviewer for SYSID 2018, SAFEPROCESS 2018 and ACC 2019.

J. Dumoulin was reviewer for EGU2018, QIRT2018 and SFT 2018

L. Mevel was reviewer for SAFEPROCESS 2018 and SYSID 2018

8.1.2. Journal

8.1.2.1. Member of the Editorial Boards

L. Mevel is member of the editorial board of the journal Mathematical Problems in Engineering, and of the journal Shock and Vibration.

Q. Zhang is member of the editorial board of the journal of Intelligent Industrial Systems.

J. Dumoulin is member of the editorial board of the journal Quantitative Infrared Thermography, and of the journal Geoscientific Instrumentation and Data Systems.

8.1.2.2. Reviewer - Reviewing Activities

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

M. Doehler was reviewer for Mechanical Systems and Signal Processing, Journal of Sound and Vibration, Journal of Civil Structural Health Monitoring, Engineering Structures.

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

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

8.1.3. Invited Talks

M. Doehler, “Détection de changements dans des modèles physiques pour la surveillance vibratoire en génie civil”, GdR ISIS, Paris on March 15th 2018.

L. Mevel, "Données, SHM et analyse statistique", SHM France meeting, Saclay, France on March 15th 2018.

L. Mevel presented a talk "Localisation de défaut dans les structures mécaniques à partir de mesures vibratoires." at Polytec Blois, on October 11th 2018.

J. Dumoulin presented a talk “Review on past to present achievements in Non Destructive Testing by active infrared thermography and current prospects” at International School of Quantum Electronics, Progress in Photoacoustic and Photothermal Phenomena: Focus on BIOMEDICAL, NANOSCALE, NDE and Thermophysical phenomena and technologies, 6-12 September 2018, Erice, Italie.

L. Ibos, T-T. Ha, V. Feuillet, S. Thebault, K. Zibouche, R. Bouchie, J. Weaytens, Z. Djatouti, **J. Dumoulin**, V. Le Sant, « Problématique de l’estimation de la résistance thermique de parois courantes de bâtiments par thermographie infrarouge : apport et limitations de la réduction de modèles », Journée thématique de la Société Française de Thermique (SFT) sur « Méthodes inverses et thermique du bâtiment: réduction et identification de modèles », Paris, 2 Mai 2018.

8.1.4. Leadership within the Scientific Community

V. Le Cam organized the 1st SHM France meeting in Saclay on MArch 15th 2018, together with CEA and Precend.

8.1.5. Scientific Expertise

V. Le Cam was involved in an expertise dealing with electromagnetic susceptibility of axle detectors for National French Railway Company (SNCF).

8.1.6. 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. During 2017, he has been involved amongst others in meetings and selection of R&D projects, PhD and post-doc funding, international mobility.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

J. Dumoulin

- Licence Professionnelle TAM : thermographie infrarouge active, 12h, Université Paris-Est, France
- Master 2 MMMRI (Maintenance et Maîtrise des Risques Industriels), contrôle non destructif par thermographie infrarouge active, 24h, Université Paris-Est, France
- Master 2 ITII, BTP, module Maintenance et réhabilitation des ouvrages, Transferts thermiques dans les Structures : Des principes physiques à l'application sur site réel, 12 h, Ecole Centrale de Nantes(ECN), France.
- Technical Skills Training for Master 2, PhD and Post-Doctoral on InfraRed Thermography : Industrial case studies IRT, at 1st Annual General Meeting of On Duty project, 5th June 2018, 1h30, Laval University, Québec, Canada.

V. Le Cam

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

M. Doehler

- 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

8.2.2. Supervision

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

PhD : 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.

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

PhD : Nicolas Le Touz. *Design and study of positive energy transport infrastructures: from thermo-mechanical modeling to the optimization of such energy systems* J. Dumoulin. Ecole Centrale Nantes (ECN), defended in November 2018.

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, since November 2016.

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.

8.2.3. Juries

Q. Zhang participated in the PhD jury of Kokou Langueh on December 6th, 2018 at Centrale Lille.
J. Dumoulin participated in the PhD jury of Lei Lei on July 16th, 2018 at Laval University Québec.
F. Gillot participated in the PhD jury of Melaine Desvaux on July 9th, 2018 at ENS Rennes.
L. Mevel participated in the PhD jury of Martin D. Ulriksen on April 20th, 2018 in Aalborg.

8.3. Popularization

J. Dumoulin presented a talk on "Surveillance thermique long terme" at Blue Day event organized by the Pole Mer Bretagne Atlantique on "Maintenance des infrastructures / Instrumentation / Suivi en service / durée de vie et prolongation / nouvelles agressions" , Brest, November 14th, France.

J. Dumoulin presented the COP21 solar hybrid road demonstrator at Loire- Atlantique event : "Inventons la route de demain", journées enseignements et perspectives, Fay de Bretagne, November 5th, France.

J. Dumoulin presented a talk "Routes à énergie positive" at Escales Génie Civil, Saint-Nazaire, November 22nd, France.

8.3.1. 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.

M. Doehler is member of Comité de centre committee in Rennes.

8.3.2. Interventions

M. Doehler participated to Journée de la science on October 5th 2018.

8.3.3. Creation of media or tools for science outreach

A damage localization mockup has been developed and installed in the showroom of Inria Rennes [43]. It has been the support of I4S presence during the Fête de la Science on october 5th, where several highschool classes were introduced to physics and statistics by means of our demonstration mock-up.

9. Bibliography

Major publications by the team in recent years

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[2] A. CRINIÈRE, J. DUMOULIN, C. IBARRA-CASTANEDO, X. MALDAGUE. *Inverse model for defect characterisation of externally glued CFRP on reinforced concrete structures: comparative study of square pulsed and pulsed thermography*, in "Quantitative InfraRed Thermography Journal", March 2014, vol. 11, n° 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° 1, pp. 084978–084978

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[8] M. DÖHLER, L. MEVEL. *Subspace-based fault detection robust to changes in the noise covariances*, in "Automatica", September 2013, vol. 49, n° 9, pp. 2734–2743 [*DOI :* 10.1016/J.AUTOMATICA.2013.06.019], https://hal.inria.fr/hal-00907662

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[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, n^{o} 1, pp. 141 - 148, https://hal.inria.fr/inria-00365991

Publications of the year

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Invited Conferences

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