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## **Informatics and Structural Intelligence: trends, challenges, research directions, applications**

F. Bourquin, Vincent Le Cam, Jean Marie Caussignac, Manuel Collet, Michael Krommer, Jyrki Kullaa, Michel Lenczner, Sylvie Lesoille, Michaël Peigney

► **To cite this version:**

F. Bourquin, Vincent Le Cam, Jean Marie Caussignac, Manuel Collet, Michael Krommer, et al.. Informatics and Structural Intelligence: trends, challenges, research directions, applications. NSF/ESF Workshop on Smart Structures and Advanced Sensor Technologies, Santorini 27-06-05, European Science Foundation + National Science Foundation, Jun 2005, Santorini, Greece. hal-04465850

**HAL Id: hal-04465850**

**<https://hal.science/hal-04465850>**

Submitted on 19 Feb 2024

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Informatics and Structural Intelligence:  
trends, challenges, research directions, applications

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NSF/ESF Workshop on Smart Structures and Advanced Sensor Technologies, Santorini  
27-06-05

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<sup>1</sup>The first author wish to thank D. Gsell, G. Feltrin, F. Derkx and P. Golterman for their helpful comments on, or inputs to, this paper

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# 1 Motivations for massive monitoring and control

European transportation infrastructures are getting old. Their ageing is expected to culminate between 2010 and 2020. Maintenance of existing infrastructures has become a priority and now costs more than the construction of new ones. But any cost efficient assessment, maintenance and strengthening process requires specific information about the current condition state of a structure. Since early detection of cracks in roads, bridges, tunnels and other civil structures is of prime interest in the context of improving safety and reducing costs, "intelligent" structures that can detect the formation of a crack are a major stake in Europe and worldwide. An ultimate goal would be to build structures that could call in an engineer or even auto-adapt to alleviate any risks generated by the forming fractures or other damages.

However, even though a crack can have a tremendous impact on the safety of the structure, the measured repercussion from a forming crack on the structure is rather small. Detecting the crack is a major difficulty, because of the subtlety of the impact, and consequently the slight change in the response is poorly measured by the sensor. Moreover, all cracks may not be dangerous, only part of the cracks is worth being monitored, but strategies are needed. A bottleneck is the lack of optimized sensing capabilities and related algorithms, or the lack of real dissemination of relevant pieces of knowledge and operational tools. Many things exist which are not routinely used if not completely ignored by practitioners.

It is now commonly accepted that Structural Health Monitoring (SHM) not only should focus on finding out emerging damages but also should provide with a diagnosis regarding the severity of the damages and with a prognosis, or prediction, of remaining life-time of residual bearing capacity [42]. According to Los Alamos report [42] and included references as well as to engineering practice, the multifaceted concept of damage spans from localized cracks to macroscopic settlements, not forgetting corrosion or chemical reactions like alkali-aggregate reaction in concrete. A typology of damages encountered in french bridges can be found in the final report of the Kronos project [2]. Generally speaking, corrosion and water related physicochemical processes appear to be the main sources of damage in civil engineering structures, at least in France, but also in northern Europe [50].

Safety issues are also urging the authorities for substantial progress in western countries. Major incidents due to failures in transportation infrastructure are becoming less acceptable. Zero-risk protection of citizens is now a long-term aspiration of governments. Operators and engineers are under pressure to make every possible effort to assure public safety. This is where monitoring comes into play, at the same time increasing operational efficiency and reducing costs.

Life extension and rehabilitation of existing transportation infrastructures, their adaptation to new traffic regulations or to versatile usages, the concept of mobile bridges in urban areas or climate change may urge the widespread use of the control of structures in the construction sector.

The need for multifunctional materials, control algorithms and wireless sensor networks stands clearly stated in the current version of the European Strategic Research Agenda for construction, according to a 2030 vision of this sector. This document may serve as a guideline for industrial needs and goals for the next 25 years.

## 2 State of the art: current practice, evolutions, technology

### 2.1 From inspection to monitoring

Assessing the condition of a structure is a key step in a global bridge management strategy (see the European project BRIME). Assessment is traditionally carried out by visual inspection and simple procedures (see European projects SAMCO for European inspection codes and practice). Additional knowledge about the structural safety is obtained by testing samples removed from the structure. Damages inside the structure that are not visible are tried to be identified by

several non-destructive localized measurement techniques, e.g. based on mechanical and electromagnetic waves and fields, and usually called Non Destructive Evaluation techniques (NDET). These techniques are put to work only when the structure is known to suffer from damages or to dysfunction. The drawbacks are the locality of the information, the cost due to manpower and equipment, and the absence of information unless a problem is already detected.

Hence the need for continuous monitoring, that help checking the design, making sure the structure behaves normally at every time, and detecting abnormalities such as fatigue, ageing, damage or actual loads that exceed design loads. This approach has already proved useful for the protection of citizens, since *e.g.* acoustic emission enabled to reliably detect cracks in stay-cables of a large bridge and to stop the bridge operating just in time. See [22] for technical details.

A steadily increasing number of permanent sensors is being installed on new bridges [64]. Great Belt bridge was equipped with less than 100 sensors, but Kap Shui Mun bridge in Hong Kong [104] hosts around 300 sensors of all kinds, including 220 temperature sensors. The future Stonecutter bridge in Hong Kong bay area will host nearly 1200 sensors [104], a third of them dedicated to temperature monitoring. Computing capabilities and up-to-date finite element software are also available for predicting and checking the behaviour of these bridges.

However, European practice of bridge monitoring does not evolve that fast. This fact is certainly due to many factors, including an old tradition of excellence in engineering, a recent trend towards safety above all, the shared responsibility between constructing companies and owners and costs as well as the lack of clear economical proof that monitoring really offers an interesting return on investment. Such proof does exist but several obstacles hinder from adequate dissemination.

## 2.2 Research policies

Generally speaking, continuous monitoring of civil infrastructure has become recognized as an important step in the assessment of the structure's health. Health monitoring and damage detection have given rise to significant research efforts world-wide. See [98] for a review. The American NSF has funded many projects in the framework of the dedicated programme *Sensors and sensor networks*. In Europe, as a counterpart of NFS incentive, ESF has recently issued a call for proposal to the Eurocore S3T (Smart structural systems technologies). Domestic programmes also exist and the french Ministry of Equipment has defined several top-priority research directions, mainly focussing on monitoring and modelling. Smart sensing is also an important topic to CNRS (french national center for scientific research).

Finally, the European Construction Technology Platform is now elaborating a document called Strategic Research Agenda where main lines of important research for construction are clearly drawn. A strong emphasis is put on monitoring and knowledge-based technologies including sensors, wireless sensor networks and multifunctional materials to quote a few items.

## 2.3 Algorithms, technologies in use

### 2.3.1 Operational modal analysis

Vibration-based structural health monitoring may become an alternative to manual inspection of civil engineering systems. The research in the field is very active involving interdisciplinary studies in structural analysis, sensors, data acquisition, system identification, information technology, and statistical pattern recognition. The technology has now developed to an applicable stage. However, the poor reliability due to the effects of the environmental and operating conditions still delays the approval of the technique in some applications. Ambient vibration measurements in conjunction with modal analysis and model update can be used to assess the global structural integrity. Practical experience on algorithms and field implementations *e.g.* on the Z24 Bridge [9] are now available. Output-only subspace modal analysis methods taking advantage of correlation matrices result in powerful online damage detection algorithms [11] and

toolboxes do exist (see [77]). other features have been used, *e.g.* spectral data or AR coefficients [53]. Statistical methods have been explored [52]. The dimensionality reduction is an important part in damage detection in order to increase the statistical reliability. The dimensionality may be reduced using the principal component analysis (PCA) [89]. PCA transforms the data matrix by diagonalizing the data covariance matrix so that the first new variables account for the maximum variance in the data. This can be used for handling the effect of temperature after a long monitoring period [59, 60, 61].

### 2.3.2 Control of structures

Passive control, including base isolation, has now pervaded the whole construction sector. Pedestrian bridges usually need control because of high flexibility making pedestrian uncomfortable if not scarred.

Shape-memory alloys are used to protect constructions from the seismic risk: the restoration of the basilica of San Francesco d'Assisi in Italy is perhaps the most striking example [32]. In the event of seism, shape-memory alloys have the property to effectively dissipate the energy received while limiting the forces transmitted to the structure. More generally, the use of multifunctional materials contributes to the rehabilitation of the built cultural heritage. In the recent years, new ideas of efficient devices for the seismic protection and the vibration control of civil engineering structures have emerged. Some of these innovative systems take advantage of the peculiar properties of SMA, namely the possibility of dissipating large amounts of energy and the capacity of undergoing large strain cycles without residual deformation. Examples of such devices include intelligent bracing systems for framed structures, damping devices for structural vibration control, restrainer cables for bridges, smart connections (like beam-column connection for instance), base isolation systems. The advantage of such SMA-based systems over traditional ones is confirmed on the (generally small- or medium-scale) experiments that have been conducted so far. For instance, some experiments on framed structures have shown that S.M.A. braces could offer better performance than conventional steel braces. Indeed, S.M.A. braces allow for very small residual displacements compared with steel braces. This "recentring capability" is due to the superelastic property of S.M.A.: for the loading considered, the response of the S.M.A. remains pseudo-elastic whereas conventional braces undergo plastic deformation and therefore display residual displacement after unloading. Other experiments on SMA restrainers for multi-span bridges [36] have proved that SMA restrainers are more efficient than conventional steel ones. Such experimental evidence clearly justify the relevancy of using S.M.A. in damping devices for regulating the transient response of civil engineering structures.

Shape memory alloys (SMA) have the ability to transform with a relatively small energy or external action between different crystallographic phases. This process is the martensite/austenite phase transformation which can be produced either by thermal actions or by mechanical actions [7], [46]. Enormous research has been performed in engineering, material sciences and mechanics on this topic. In engineering and thermo-mechanics, shape memory alloys may be described at various levels depending on the engineering applications. The macroscopic level deals only with the macroscopic displacement, the mesoscopic level deals with the macroscopic displacement and quantities averaging the microstructure (involving, in particular, the volume fractions of the phases). The microscopic level deals with the displacement whose gradient oscillate at the microscopic level. The three preceding models are continuum theories. The finest scale is the atomic level. The essential problem of these multiscale modelling is to involve suitable information of the microstructures such that their influence is taken into account in the model without describing the microstructure in detail. The importance of the suitable information depends on the application. Thus modelling depends on the purpose and the application. There is a large literature on modelling at all the levels. A survey of the wide menagerie of SMA models may be found in [87], [7]. We conclude that multipurpose models are available for engineering applications, in particular for civil engineering applications.

On the contrary, active control is used in a permanent way on a very limited number of important buildings. It is also commonly used during construction of large flexible structures such as bridge piles [63] but active systems are generally removed after the construction is completed. There is so far no clearcut application of permanently installed purely active systems on bridges although large-scale experiments in Ispra in the framework of the European project ACE [74, 15] have shown the relevance of the approach.

However, semi-active control schemes start to emerge as a way to mitigate wind-induced vibrations in cables, especially in China.

### 2.3.3 Optical fibre sensors

Optical fibre sensors (OFS) are made of an optical fibre attached to (or embedded in) a structure to be monitored, and of an opto-electronical interrogation unit [5], [12], [96, 97], [33, 57]. They take advantage of the way guided light is influenced by the geometry and stress state of the guide. When an Optical Fiber Sensor is subjected to a mechanical solicitation, its optical length  $nL$ , where  $n$  denotes the refraction index and  $L$  the length of the sensor, varies according both to the geometrical change of the sensor and to the photoelastic effect. Typical simplified expressions involving the refraction index to stress dependence in such a sensor [102] can be found *e.g.* in [106]. Non-linear 3D finite element analysis can be found in [10]. Assuming sufficient kinematical or statical transmission from the surrounding medium to the optical fibre takes place, the accessible light parameters such as phase, polarization or intensity attenuation will inform on the strain or stress state of the structure under monitoring.

The advantages of OFS over other sensors are numerous. The main one is probably the electromagnetic immunity, not forgetting the possibility to carry out measurements along the entire fibre, as well as the possibility to use a remote interrogation unit that may be shared by several bridge monitoring systems at different locations. Moreover, many types of measurements can be carried out with an OFS. As a matter of fact, the sensor results from an interrogation principle combined with a special mechanical packaging of the fibre selecting a physical principle to be mainly active [26]. The European Union has funded several projects such as COSMOS, MONITOR, DAMASCOS and MILLENIUM on optical fibre sensors. Recently, NSF has also funded several projects on this topic in the framework of its special programme on *sensors and sensor networks*. Several conferences such as *SPIE meetings on smart structures*, international as well as European workshops on structural health monitoring, and world as well as European conferences on structural control take place regularly and include a large number of talks dedicated to the application of fibre optics technology to new sensing principles. Many kinds of optical fibre sensor systems, including commercial ones, have emerged in aeronautical and civil engineering. The literature is very abundant : see *e.g.* [95], [37] [43], [78], [90, 44], [94], [72, 76], [47]. A few examples are mentioned below.

A first idea consists of detecting a structural crack when the light stops propagating in the fibre [86] or gets strongly attenuated [81].

On the other hand, a pressure sensor is achieved by just laying out a fibre between two staggered combs, the shift corresponding to half the space period of the modes of propagation, typically about 1,3mm for standard multimode fibres. A pressure on the comb yields microbending [103] in the vicinity of contact points, and thus modifies the attenuation of guide. Bridge bearings have been equipped with such sensors in view of real-time truck load monitoring [28], or prestressing monitoring.

An other possible conditioning consists of favouring a uniform but anisotropic stress state, linearly depending on the applied external load to monitor. In this case, photoelasticity induces birefringence and thus modifies the polarization of the light propagating in the fibre. Thus a polarimeter enables one to quantify the stresses in a direction orthogonal to the fibre [13]. This load sensor has been applied to weigh-in motion of vehicules on roads [13]. See also *e.g.* the European project WAVE.

But OFS can also be used to detect chemical species [1] or to measure distributed temperature. The significance of OFS in the world of sensing appears in [33, 57]. *Pointwise* OFS essentially based upon Bragg-gratings Michelson interferometry and Fabry-Perot cavities [100, 83] are largely commercially available, as they found applications in material sensing and oil industry for examples. They mainly yield local strains, in the same way as conventional strain sensors.

On the opposite, *continuous* OFS are still confidential technologies even in structural monitoring, although the ability to realize fully distributed measurement is a primary advantage of fiber sensors over traditional sensors. Integration of fiber optical sensors in concrete structures may thus offer the opportunity to get a distributed image of the strains in a structure. Distributed sensing relies upon different optical techniques [85] among which are optical time domain reflectometry [101, 68], Raman and Brillouin scattering [56, 79, 108]. Interferometric very long-gauge optical sensors [57, 107] could also be very useful in civil engineering, especially in dynamic evaluations if they were continuously bonded to the structure following a curved arc length : it was proved analytically [16] that two long gauge embedded OFS equipped *e.g.* with a Michelson interferometer can be combined to achieve a low-frequency modal sensor of a slender Euler-Navier-Bernoulli beam provided one OFS is located at a distance from the neutral axis proportional to the curvature of the target mode. Similar results hold for piezo-electrical cables.

### 2.3.4 Wireless sensor networks

Wireless sensor networks have recently attracted the attention of a lot of teams. Industrials also propose commercial wireless solutions. However, very few are really implemented for real-life monitoring (see however an example at the end of this paper). The main focus of University teams has been on autonomy, not on matching application needs. This is probably due to the will to adapt new wireless technologies to a traditional way of implementing monitoring systems, where sensors send continuously a lot of raw data to a central processing unit. These endeavours led to proprietary protocols optimised from the viewpoint of energy consumption. But this kind of system usually suffers from several strong limitations regarding the versatility, *i.e.* the possibility to change the sensor network at any time by just adding, moving or removing heterogeneous sensors. Data flow rate and maximum distances between sensors are also limited. This is probably part of why Intel is exploring embedding motes into a system that implements high level protocols. The authors are not aware of any similar industrialisation in Europe so far but this may change very fast. However, other already operational and promising avenues based on a completely different monitoring scheme are reported at the end of this report. They enable taking advantage of both network functionalities and powerful local computing.

## 3 Technology barriers

### 3.1 Environmental perturbations

There exist various strategies to detect damages in a structure : among others, a very attractive and promising class of techniques relies on the monitoring of ambient vibrations. These output-only methods consist of either identifying the current low-frequency spectrum of the structure that may have undergone some damage, or checking that some vector still belongs to the kernel of the Hankel matrix made of covariance matrices of measured outputs [11]. In both cases, the undamaged or reference structure is supposed to be known, which is the case for every new bridge for which a rather accurate mechanical model is usually available at the end of the construction works. Operational modal analysis or online damage detection aim at detecting spectral changes. Of course, not every damage may change a given eigenfrequency in a significant way, moreover a significant frequency shift indicates the structure is close to collapse, therefore eigenfrequency monitoring may yield to late answers in view of structural health monitoring. However eigenmode curvatures [31, 30], and, even better, a subspace spanned by several



eigenmodes prove much more sensitive to slight damages. Of course the dynamical behavior of the monitored structure may be affected by several possible factors, including temperature changes [84]. As a matter of fact, depending on boundary conditions and temperature distribution, thermal variations may cause very significant changes in the spectrum of the structure [42] because of additional prestressing. Temperature may even modify the boundary conditions and change the number of contact points between the piles and the bridge deck. As a matter of fact, temperature may be as important as the bridge dead load [34]. Thus environmental effects may be several orders of magnitude larger than the effect of structural damages.

Therefore, as mentioned in [42] and many other papers, it is mandatory to eliminate the thermal effects. Environmental compensation appears as a real bottleneck in this field. Most attempts in this direction have favoured a blind approach aiming at finding out correlations between strain sensor outputs and external temperature [42, 54]. Temperature thus appears as a parameter that should be rejected from a model that only takes into account dynamics of structure. See [59, 60, 61] for the use of principle component analysis, based on the correlation between the observed features. The training data should include at least one complete cycle (if any) of in-service conditions before applying damage identification. Moreover unusual or exceptional environmental events may not be taken care of in a suitable way.

A complete multi-physical monitoring combined with thermomechanical inverse modelling may eliminate in real time the adverse thermal effects from the measured data as reported in the contribution to the roadmap below.

### **3.2 Shape memory alloys**

For the regulation of the transient responses of civil engineering structures, it seems reasonable to focus on macroscopic and mesoscopic models. Let us mention that some of the most attractive models of this type are due to scientists involved in the project, [7, 14], [46]. The models depend on some parameters, many or few, easy or difficult to measure or to estimate. The available models have to be tested in accordance with the different applications, in particular with civil engineering applications. Some of the models have already been used for engineering purposes [7]. The properties of SMA, mainly their dissipative properties make them promising to control transient response or to dissipate their energy [3], [23], [36], [38], [105]. As far as we know there are few practical applications. For civil engineering applications no large scale experiments and validation have been performed. It results that no robust and validated construction rules are available. Some actual applications for energy dissipation of earthquakes have been performed [32]. It appears clearly that the development of civil engineering applications has to be based on experiments in large scale facilities devoted to civil engineering in cooperation with predictive theories which will make possible the extrapolation of the results and the production of basic construction rules.

### **3.3 (Micro)mechanics requested**

But the technological advances in terms of sensing capabilities and signal processing have put forward the need of fundamental understanding of how the sensors really interact with its surrounding medium in the structure to be studied. Complexity is due to the heterogeneous constitutive material or to non-linear behaviours (plasticity, friction, damage) sometimes localized at connections. Sensor downscaling enabled by micro- and nano-technologies thus urges a need for interpreting the sensor outputs in agreement with the mechanical description of the structure at the micro- or mesoscopic level. This is especially true for granular materials such as concrete or soils where Cauchy continuum may be replaced with Cosserat continuum which accounts for local orientation [88]. There exists a computable minimal representative elementary volume for Cauchy continuum to hold in the case of heterogeneities [8]. In any case, multiscale analysis may help extracting macroscopic quantities of interest from small-scale sensors.

Generally speaking, assessing by means of reliable methods the quantities of final interest on the basis of available indirect measurements becomes a real challenge. In this wide area, enabling technology may be a subtle combination of physics for the basic mechanisms, mechanics for the macroscopic modelling in view of prediction, and mathematics for the suitable formulation of the problems to be treated and the reliability of numerical algorithms.

### 3.4 Lack of an *ad hoc* computational framework

There is an agreement in the international engineering science community that smart microsensors with embedded microprocessors and wireless communication links have the potential to change fundamentally the way structural systems are monitored, controlled and maintained. Quoting [48], "ubiquitous sensing is becoming possible provided that ubiquitous sensor networks operate on the vast amount of data generated in order to return decisions and information. Therefore, the convergence of sensor technologies, communications, and computing has the potential to overcome barriers of time, scale, materials and environment. This level of system integration is called Sensor Informatics". A good overview on the ongoing research in Europe and the USA on smart sensor technology, particularly concerning the application to structures of civil and mechanical engineering, can be taken from the Proceedings of several joint ESF-NSF workshops [41, 91] and European Conferences on structural control [24], [25]. See also [82]. In a recent review on corresponding opportunities and challenges [62] it is stated that current algorithms utilized for smart sensors usually do not yet scale to sensing systems with densely instrumented arrays of sensors that will be required for the next generation of health monitoring and control systems. In [62], a number of critical issues have been mentioned that are needed to be resolved, before the opportunities offered by modern smart sensing can be utilized : besides some hardware issues, a lack of computational framework on which to build new strategies for realizing massively distributed smart sensors has been stressed.

### 3.5 Design issues

Very often, sensor placement and the whole instrumentation scheme is based on experience, at best. This is not necessarily a satisfactory approach for various reasons: nobody has experience on novel structures. Experience becomes unavailable because of increasingly dynamic professional carriers. Experience can hardly end up with complex quantitative decisions. On the contrary, rational design of increasingly complex monitoring system may take advantage of advanced modelling and optimization concepts, that would not only address structural mechanics to be short but also sensor characteristics, geometry and placement as well as smart sensor output processing, dataflow, communication schemes, reliability ... Scientific fields of interest include of course mechanics physics and scientific computing but also information theory, system theory, network theory ...

### 3.6 Optical Fibre Sensors

A major difficulty that is slowing down the development of distributed optical fiber sensors is the strain-field transfer from the host material to the embedded optical fibre [85]. Materials and their bonding characteristics [4, 71], [55, 39], [27, 19] as well as shape [45] of the sensors strongly influence the difference between the strains in the optical fibre and in the concrete, and more generally, the sensor response. There is a need for a special packaging of the optical fibre meant for attaching the fibre over very long distances and continuously to the concrete [49]. To do so, several solutions have been proposed and analysed. Anchoring the sensor at both ends [45, 29, 73] requires to pay special attention to debonding issues [45] and material stiffness matching [4, 71, 55]. In view of improving the kinematic continuity between the sensor and the surrounding medium over long distances, wave-like sensors have been proposed and evaluated both by 3D linear finite element analysis and experimentally [35]. In this field, one may predict

the strains in the structures for example by just inverting the opto-mechanical coupling. This partially open and computationally intensive approach may boost the use of optical fibres as distributed sensors integrated into the structures.

### 3.7 The curse of wiring

Today, most if not all of the existing, temporary or permanent continuous monitoring systems for civil structures have serious drawbacks. The sensors are most often connected by cables in a star topology, *i.e.* every single sensor has to be connected individually to a central data acquisition system. The extensive wiring may contribute more than half of the whole cost of monitoring. Moreover it may just prove impossible to realize when for example long bridges have to be monitored. Due to the wires, conventional monitoring systems are susceptible to failure because of possible cable cuts, leading to loss of data and interruption of the continuous monitoring process. Moreover, electromagnetic coupling between multiple cables make sensor outputs very noisy. Finally, wires hinder from massively distributed instrumentation and negatively impact on the durability of monitoring systems. Of course, to achieve electromagnetic immunity, field buses (HART, FIP, Lonworks ...) are also put to work to carry digital information from intelligent sensors to a supervisor, but they do not offer much flexibility since they are based on special purpose dedicated low-level protocols. Moreover, these networks require intelligent sensors equipped with conditioning, analog to digital converters and signal processing capabilities.

As mentioned above, currently existing wireless sensors platforms suffer from limitations that seem to call for another monitoring concept.

In any case, energy autonomy remains a partly open problem in several applications, especially if high-level communication protocols are put to work. Scalability, flexibility and durability issues are usually not addressed.

## 4 Contribution to a roadmap for Smart structures and Sensor technology

### 4.1 Towards aerial inspection of bridges and pavements

A research and development activity focusses on the possibility and way to use unmanned aerial vehicles (UAVs) for bridge inspection [40, 80]. A national project in the framework of the french Urban and Civil Engineering Network involving industrial and academic partners, and one specific government incentive are running. A feasibility demonstration has already been successfully completed on a bridge undergoing dense traffic. Among the various aspects to be addressed, smart image processing taking advantage of the kinematics of the vehicle [99] to determine visible cracks [93], as well as potentially embarked sheorography [19] should be addressed. Also of interest in this spirit are the optical methods and image processing technologies dedicated to the fast and automatic assessment of pavements .

### 4.2 Combining inspection and monitoring

Moreover, very often, heavy, visual and thus superficial, and occasional bridge inspection is presented in contrast to blind but sensitive, cheap and continuous monitoring. This contrast might be smeared in the future. As a matter of fact, visual inspection may take advantage of new technologies such as CCD camera on board of Unmanned Aerial Vehicules that should lead to enormous savings as well as to drastically enhanced flexibility. It can also be combined with physical means of detecting non-visible potential damages. Therefore, ubiquitous continuous inspection might become an affordable dream.

On the other hand, instrumentation for monitoring can also be a sensing system with occasional and at least discontinuous operating scheme. This is a way to carry out discontinuous monitoring with permanent sensors.

Now combining UAV based inspection on a frequent basis and monitoring systems seems to be of interest. The monitoring system should more or less automatically guide inspection efforts wherever needed. Moreover the inspection vehicle may help maintaining the monitoring system.

### 4.3 Identification of thermal prestressing for vibrating structures

As already mentioned, the temperature plays a major role in the redistribution of the stresses in the structures, affecting at the same time the static deformations and the modes of vibration. However the purpose of operational modal analysis and the static monitoring of bridges are in particular to detect sudden or progressive dysfunctioning of the structure at a given moment, by comparison with initial measurements on the same structure, under possibly different climatic conditions. It is thus important to predict in real-time the deformations or eigenmodes whom one would have measured on the same structure under the initial climatic conditions. This is particularly important for young concrete structures. Thus the comparison of the corrected values should enable one to detect a variation in the structure itself (creep, pile settlement, crack) or of its loadings. It is about a major stake on which the SHM community works for a long time without having issued convincing methods. The difficulty lies in the great amplitude of the heating effects, sometimes higher than the deformations due to the actual weight, as regards the bridges, and most of the time quite higher than the effects of the damages themselves. As a possible approach, precise and rapid assimilation techniques based on models including diffusion, exchange and radiation, for an elastostatic or vibratory prediction under thermal prestressing is worth being mentioned. Fast algorithms based on dual formulations, well-suited Fourier-Galerkin approximation techniques, and Krylov reorthogonalization should help achieving this goal. Methods are sought to correct *in situ* measurements in view of damage detection algorithms or even active or semi-active control. Predictive models and experiments in climate chambers may become important ingredients of the approach.

### 4.4 Hybrid formulations for stable model-based control laws

When it comes to design a model-based control law for a mechanical system, the choice of the model seems to be crucial. Moreover, for a given model, the mechanical formulation has proved a useful design parameter : hybridization of primal and dual control design leads to very stable control laws for simple structures at least [17, 18]. Variants include primal-acceleration hybridization. The idea can be viewed as a way to carry out frequency dependent data fusion between the outputs of the real sensors and the outputs of artificial sensors in view of decreasing modal spill-over. Theoretical results substantiating this approach are not available but would be of interest to promote a general purpose robustification algorithm for model-based control laws.

### 4.5 Damping modelling and pseudo-differential operators

The necessity to observe a wide band of structural damages involves the use of semi-distributed sensors correctly managed by well shaped algorithms. The importance of the optimizing procedure is also clear. However a crucial difficulty still exists in our ability to model the medium frequency responses of structures extremely sensitive to localized damages or modifications of the system. Indeed, from a scientific point of view, between the typical modal behaviour of the low-frequency domain and the statistical behaviour observed in the high-frequency range, there is a zone called medium-frequency domain in which no approach, neither numerical nor experimental, is really satisfactory. In this domain the mechanical damping operator appears of

major interest because it drives the response of the structure. Here all the classical representations of this damping effect based on Basile assumptions are not suited and cannot model the physics of the involved phenomena. A new and very attractive way to deal with this problem is to introduce much more elaborated damping operators as pseudo-differential operators [75]. Specific numerical approaches have to be improved to be used in detection algorithm or in expert systems [6]. The potentialities of such a method are very large and range from active control to numerical methods [51] and constitutive laws. They could also be used for operational health monitoring techniques.

## 4.6 Cellular Neural Networks

Cellular Neural Networks (CNN) answers the question of embedded intensive computation based on networked computers. Potential applications are in many fields of physics where intensive calculations have to be made in real time with embedded computers for the treatment of arrays of data. Let us mention a few of them: detections of moving acoustic sources, control of acoustic noise, vibrations damping, control in fluid mechanics, measure of brain activity, radars, etc. In most of applications that require intensive embedded computations, DSPs networks are employed. An alternative hardware solution is now emerging, the so-called Cellular Neural Networks (CNN) technology. The original idea appeared in the celebrated pioneering paper of L. Chua [2]. Since this visionary work, much time and energy have been spent to develop this new technology that become more and more mature. Today-applications are mainly oriented towards image processing with a large spectrum of potential industrial application. However, we think that, in the next decade, we will assist to the emergence of a large variety of applications in many other fields. A Cellular Neural Network is an array of interconnected analogic processors (see T. Roska and L. Chua [3] for details). Today available CNN chips have 128x128 analogic interconnected programmable cells. The basic operation (or instruction) in a CNN consists in solving a system of (non-linear) differential equations with as many variable as cells in the array and with programmable coefficients. These coefficients are spatially invariant and are so that they couple each cell with their closest neighbors. With such an architecture, realization of finite difference operators associated to one-dimensional or two-dimensional finite difference equations is an easy task. Additional basic instructions which produce local simple algebraic operations as additions or multiplications may also be available. A CNN can also execute a sequence of elementary instructions. Its input and output data are arrays of numbers. The huge advantage of the CNN computers is that a basic instruction operates on a very large amount of data (128x128) in an extremely short time (a few nanoseconds). This is for example the time required for the resolution of the Laplace equation.

Recent unpublished works by M. Lenczner and G. Montseny address the problem of the concrete realization of linear operators on infinite dimensional spaces in a way that be compatible with real time and embedded computation, possibly implantable on such CNNs, i.e. that requires only the few possible operations already mentioned.

Other authors have already studied the same kind of question. B. Bamieh and its co-workers have developed in [1] a method that produces approximate realizations of operators. It furnishes, when it exists, an approximation under the form of a convolution product between the input and a kernel having a small support. Their method is limited to a class of space invariant operators, which excludes optimal control on bounded domains (in particular the case of boundary control or boundary observation). For the same class of problems, the authors have built in [4] optimal approximate realizations based on combination of finite differences operators. The coefficients of the approximate operator are obtained from numerical resolution of Linear Matrix Inequalities (LMIs), which have not always a solution. The authors announced that their method could be extended to bounded domains and also to boundary control or observation. In [5], the authors have built an approximation in the sense of high frequencies, by means of a cascade of partial differential equations. At the moment, this method is restricted to operational equations whose

coefficients are all depending on the same partial differential operator. It turns out that it cannot handle the kind of operators that we get in optimal control theory when observations or controls are on the boundary (or concentrated on some particular point in the domain). Both methods developed in [4] and in [5] suffer from some strong limitations that are now overcome by using the **diffusive representation** concept.

The nice feature of the so-called *diffusive representation* concept [7, 9] is that it converts causal linear integral operators in a series of basic linear ordinary differential equations of diffusion type the solutions of which are then weighted by a diffusive kernel and simply summed up in real time. The concept reveals well suited to the state-space realization of linear integral operators, like Riccati operators, on parallel architectures like CNNs.

The theory of diffusive representation and its applications have been broadly developed in [9] and the references therein. They have been reported in a recent monograph [7] in which a general framework is introduced and applications covering a large range of fields are presented. One of the main recognized advantages of the diffusive representation is the low computational cost of concrete realizations of integral operators derived from this approach (see for example [6]). Until now, a large part of the studies have been focused on one-dimensional problems where the operators were given explicitly. However, in many cases, the theory can be extended to any dimension (see for example [7] where diffusive realizations of an nD-operator are introduced and applied to a problem of image processing).

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## 4.7 Modelling

Generally speaking, sensor intelligence assumes sensor know what they are supposed to sense, and how the quantities of interest behave. This means that sensor design and exploitation should rely on a deep knowledge and quantitative modelling of their surrounding medium. Moreover, downscaling is an issue that is relevant to distributed intelligence since a small-scale sensor may have access to quantities that are not directly or not yet of interest because monitoring algorithms may not be able to take advantage of them.

Moreover, if dynamics of structures is a well established field that can now host monitoring concepts and tools, many damages do not fit in this framework and accelerometers or tiltmeters may not be of interest to evaluate residual bearing capacity due to corrosion for example. Multiphysics is thus called up to help designing sensors and associate signal processing capabilities.

#### 4.8 Modal and indirect sensors, optimal placement and geometry

Model-based control algorithms as well as operational modal analysis in view of Structural Health Monitoring may take advantage of band limited sensors. As a matter of fact, model-based control law require a projection of the dynamics onto a finite-dimensional space, usually made of eigenmodes, and therefore ideal sensors should deliver the projection of the true dynamics on the same set set of modes. Non-ideal sensors lead to "observation spill-over", because the best possible combination of sensor outputs includes part of the unwanted or "unmodelled" dynamics. Ideally, actuators should also excite the same modes only. Whenever they cannot, they lead to control spill-over. The combination of observation and control spill-over potentially leads to spill-over instability, depending on the control gain and structural damping, and no matter the control law or the controllability of the structure. This well-known difficulty severely limits the practical interest of model-based control algorithms. However, large-scale applications of this kind of control to mitigate the vibrations of bridge piles under construction or even tall buildings are reported [63]. Since ideal sensors or ideal actuators are sufficient to prevent from spill-over instabilities, research efforts are naturally directed towards sensors aiming at preventing from observation spill-over.

On the other hand, a band-limited sensor may also help detecting cracks or other damages. Hence the interest of modal sensors that only sense the time-dependent participation of a single mode in the global transient response of a structure. Several examples of necessary distributed sensing enabling the construction of approximate modal filters already exist.

Very long base OFS provide with the capability to capture global kinematic features of the surrounding structure. It was proved analytically [16] that two long base embedded Optical Fibre Sensors equipped *e.g.* with a Michelson interferometer can be combined to achieve a low-frequency modal sensor of a slender Euler-Navier-Bernoulli beam. Extensions to general structures should be undertaken. Moreover the analysis might be extended to the indirect measurement of displacements, slopes or curvature gradients at certain locations. To this end, shape gradient techniques or level-set approaches may help, as well as photoelastic modelling.

Although the most prominent method for measuring the structural response in infinite-dimensional systems is the use of necessarily distributed modal sensors, there are many other structural entities that are of interest in structural health monitoring and control. These entities can be either of the kinematical type or of the dynamical type. In case one wants to measure a specific kinematical entity the distribution of the sensing must be such that the sensor signal does not contain any other content than the desired one. Modal sensors are an example of a sensor measuring a specific kinematical entity. The total displacement of the structure is expanded into a series with the eigenfunctions as basis functions. A proper choice of the distribution of the sensor (proportional to the gradient of the desired eigenform) ensures that only one modal amplitude is measured; the reason is the orthogonality of the eigenfunctions. However, the modal decomposition of the displacement is not the only one possible. A different approach may consider a Helmholtz decomposition of the displacement vector into a divergence free part and into a solenoidal part. Again, a proper choice of the distribution of the sensor will result into the measurement of the dilatational part of the displacement only (for that sake the sensing must be a spherical tensor) or into the measurement of the rotational part of the displacement only (in this case the sensing must be a skewsymmetric tensor). Other examples would be problems, in which one is only interested to resolve parts of the motion that are superposed upon others; *e.g.* to measure kinematical entities relative to prescribed rigid body motions, to measure kinematical entities relative to large static deformations or to measure these

entities relative to a desired displacement field of the body. Moreover, in many applications we may only be interested to measure the kinematical entities in a sub - domain of the structure. The latter case is interesting, whenever we know a priori, where the critical domains of the structure are located. One interesting aspect is that, if the structure is redundant distributions of sensors resulting into the measurement of a desired entity are not unique. There are always non trivial distributions (those that coincide with stress distributions in redundant structures in the absence of any force type loading) for sensors that measure nothing; these are denoted as nilpotent sensors. The usefulness of such distributions is that they can be added to any other distribution without changing the behavior of a distributed sensor; this additional degree of freedom in the sensor can be used to further optimize distributed sensors. Sensors measuring kinematical entities are widely used. In contrast there is a lack in designing sensors, which are able to directly measure dynamical entities such as stresses (internal forces) or body forces and tractions (external forces). The development of a theoretical basis, on which these sensors can be designed is one of the future key aspect in structural control [66], [65, 67], [58]. The latter type measuring external forces could lead towards eliminating the structural response due to these forces by a proper counteraction; on the other hand sensors measuring internal forces could be used to directly detect locations within the structure with a high probability for a failure. Therefore, dynamical sensors could pioneer the sensing of crack initiations, which are known to be the main cause for structural collapse. Structural stability and safety could be improved, the structural components life-time could be extended and lightweight structural components in numerous fields of construction engineering could be leveraged.

Successful endeavours in the indirect measure of a mechanical quantity of interest should also pave the ground to a new type of collocated control. Although many variants do exist, the usual way to look at collocated control includes pairs of sensors and actuators, each pair being placed at a single location. However, in practice, sensors and actuators should not play the same role since, on a large structure at least, one may easily spread out a huge amount of (wireless) sensors but much less flexibility is granted to actuators since e.g. cost, energy requirements, possible places to attach them to the structure are very different. Hence, why not shaping a continuum of sensors yielding an output which would be perfectly collocated, in the sense of Green's formula, to a given actuator ? In this case, one would take advantage of both inherent stability (or passivity) of collocated control systems and the possibility to use completely "discollocated" unbalanced and heterogeneous populations of sensors and actuators. This concept of "discollocated truly collocated" control only rephrases and slightly extends an idea of Prof. Irschik.

In addition to the optimal lay-out of curvilinear sensors, optimal placement and weighting of a very large number of point-wise sensors will be tackled, from an unusual viewpoint: finite element theory. Integral representations of desired sensor outputs (in the main stream of JKU research achievements) make it possible to express a problem of sensor placement as a problem of numerical integration with a non-standard weight [21, 20]. In principle, sensors should be placed at the Gauss points of the quadrature formula, which weights are the optimal weights of sensors. Existence and practical characterization of such quadrature formula for mechanical systems of interest is the open question to be solved. The answer contains the sensor placement algorithm. The problem has been solved for beams under traction where an explicit solution was found but the extension to general structures is to be done.

## 4.9 Optical Fibre Sensors

Today, Optical Fibre Sensors are mainly used as local strain sensors such as Bragg gratings or as information carriers, but seldom if ever as sensors delivering information distributed on the medium in which one can embed them. In this field, one would primarily wish to predict the strains in the structures for example by just inverting the opto-mechanical coupling. This potentially computationally intensive approach may pave the ground to the reliable use of optical



fibres as distributed sensors really integrated into the structures.

Truely distributed ( i.e. continuously sensitive over all their length) sensors based on Brillouin effect develop today, but many difficulties remain, in particular the reproducibility and the sensitivity to the surrounding medium which make the calibrations extremely difficult. More classical optical principles such as OTDR (Optical Time Domain Reflectometry) could prove very interesting. Nevertheless, new photonic crystals optical fibres should extend the potentialities of the associated sensors considerably. The feasibility of sensors based on these new fibres for applications as different as extensometry, measurement of curvatures, or chemical species is still mostly open.

Integration of fiber optical sensors in concrete structures may thus offer the opportunity to get a distributed image of the inner strains. This intrusive use of OFS should rely on a deep understanding of the optomechanical coupling and in particular of the mechanical coupling between the coated sensor and the surrounding medium. Direct and inverse modelling should prove very useful in the design of a fully integrated and distributed sensor. Conditioning plays a crucial role in the development of optical fibre sensors. The physical principle and the conditioning need be designed at once. This approach calls for multiphysics computational capabilities as well as optimization algorithms, which might bring a very significant added value to distributed optical instrumentation as far as the design of the optical fibre sensors and their signal processing are concerned.

#### 4.10 Exploiting network functionalities for monitoring

Wireless sensor networks, preferably based on open protocols, are not only a way to reduce costs, but they really appear as a necessary enabling technology for versatile and durable Structural Health Monitoring. In order to take full advantage of wireless sensor networks, the sensor nodes have to be energetically autonomous and they should require as little as possible maintenance. Since data transmission is highly power consuming and the recorded data for long-term monitoring is extensive, smart data reduction on the sensor node, whenever compatible with monitoring goals, as well as possibly application-dependent energetically efficient communication strategies, energy harvesting or efficient energy storing are key technologies in view of practical implementation.

Additionally, one may take advantage of new low power microsensors (MEMS) that can be embedded into the material without modifying the global behaviour of the structure.

Moving from the traditional hierarchical star-shaped concept of monitoring to a network concept, the communication between the sensors and the supervisor may not be so intensive, provided the intelligence is truely distributed in the network. Smart sensors integrating a signal conditioning a DSP an embarked OS such as linux, and a high level communication protocol send relevant informations, and not raw data, only when needed. Distributed intelligence enables one to implement event-driven monitoring schemes where the sensors decide when to send information. This concept is intrinsically energetically efficient in several cases. In general a weakness of high-level high rate wireless protocols is sensor autonomy. But this is an issue on its own which has its dynamics of progress : breakthroughs in battery technologies are possible in the near future, as well as energy harvesting strategies, as the one investigated in Pavia for the monitoring of vibrations. With high-level communication protocols, when the sensors have to exchange information permanently, long monitoring periods are actually not possible. However long monitoring periods are possible if limited information has to be exchanged within the network, because sensing and computing does not cost anything in comparison to communicating. This situation occurs in the special case of event-driven monitoring or monitoring of local phenomena provided that sensors are intelligent (sense and compute). But in general, *ad hoc* strategies must be found and put to work. This is a question of sensor informatics. A possible avenue is a systematic use of duality techniques as a mean for solving inverse problems in the *sensor space*. Lack of autonomy may thus induce algorithmic progresses and enhanced local

sensor intelligence.

## 5 Type of required expertise, researchers and industries

For sure, well-established sciences such as mechanics, mathematics, computer science have to play a key role in defining the sensor system and data processing not forgetting the data transfer scheme. Microelectronics, informatics,

Of course, new avenues can be paved by researchers who collectively or individually master more than one discipline.

There is no way to depict here the whole set of subdisciplines that truly contribute advancing the state of art in *Informatics and structural intelligence* which is not widely recognized as a field of research. The same difficulty holds for research teams also. As a matter of fact, the keywords do not prove to be suitable pointers to the teams currently or potentially involved.

Gathering all submissions to the Eurocore S3T as well as all proposals to FP6 NMP priority and collecting the list of partners could be viewed as a first step towards identification of the main actors in this area. But this objective lies far beyond the scope of this report. Citing CEA/LETI, University of Valenciennes, FEMTO, LAAS, IEF-Orsay and ESIEE in France, CSEM in Switzerland or VTT in Finland would not be so informative and would certainly hide a large number of teams actively contributing to this field in Europe.

## 6 Short term applications

### 6.1 Operational wireless acoustic emission monitoring

A wireless acoustic emission sensor network is being developed at LCPC in view of cable monitoring. It is based on a high-level communication protocol (TCP/IP) enabling either wired or wireless implementation in a transparent way, as well as high data transfer rate as well as easy modifications or the sensor number nature and lay-out. Scalability is granted by the type of protocol as well as durability in the sense that the monitoring system will be independent of the type of sensor, and then will survive technological advances in the field of measurement and distributed computing. The monitoring system will in principle be able to host every technological upgrade of every component. Durable instrumentation is an issue in bridge monitoring due to life-cycles spanning over decades. Such a wireless system has been developed at LCPC as an advanced prototype that can resist on-site implementation. A testing campaign on Merlebach bridge being dismantled in France showed both ease of implementation and excellent agreement of the monitoring results with the results of the destructive tests carried out independently. Of course the application considered is not highly power demanding. However, the process may be viewed as a preliminary step towards energy sparing systems based on the same kind of open architecture. But of course other choices in the OSI model such as ZigBee may be wise.

### 6.2 Wireless thermal monitoring

Next application considered at LCPC will be permanent thermal monitoring which is a very important issue. Here the time scale is large, this should help sparing communications, but diffusion means that no sensor has a global view of the temperature field, contrary to the case of acoustic emission in cables. Therefore it is planned to combine inverse heat transfer and a wireless temperature sensor network. The object-oriented network management software may even enable one to distribute the whole computation over the network.

Further applications regarding vibration monitoring will also be considered. In this case the question of energy sparing may be asked in terms of energy harvesting.

### 6.3 Road-vehicule communication

Based on the same principles and tools above, a prototype system enabling easy and wide-band communication between infrastructures and vehicules has been realized and tested.

### 6.4 cooperative inspection and monitoring

rechargeable battery operated wireless sensors may be a temporary solution to energetic autonomy if sensors batteries charge whenever they receive special purpose radiations emitted by UAVs moving all around the structure on a variable frequency base.

## 7 Long term applications

### 7.1 ASR monitoring

The monitoring of physico-chemical state of structure urges to model the complex interactions between the chemistry and the mechanics of the structure as in the case of Alkali Silice reaction [70], [69, 92]. Such an approach combines thermochemomechanical modelling and field measurements. But this kind of multiphysical approach should be extended to corrosion monitoring among other phenomena.

### 7.2 European SRA

The European Construction Technological Platform (ECTP) acts as a sectorial forum where construction companies industries and research centers or individuals think of the future needs of the society and the profession. ECTP has issued a prospective document, called Vision 2030, taking into account societal needs such as sustainability as well as exogeneous factors such as climate change. This document is now being supplemented by a Strategic Research Agenda (SRA) that pinpoints the main research area to focus on for the next 25 years. It is not our purpose to explain its content in details. However a few items are worth being quoted.

International competition put the construction sector under pressure to integrate the most recent technological advances and to transform into a knowledge-based industry.

The report stresses introduction of information technologies at all levels of the construction process and life cycle of the structures, such as advanced modelling and simulation, automation, advanced embedded electronics, wireless sensor networks, intelligent sensors, advanced monitoring techniques, satellite positioning ...

Moreover, the report states the need for multifunctional or added-value materials, sensors and actuators that anticipate human perception, durable materials with predictable service life including self-assessment and innovative non-intrusive in-situ inspection techniques.

Regarding networks, emphasis is put on the real-time control of operations in view of safe utility concept, information exchange between infrastructure and operators.

Maintenance, upgrade and retrofit of the European assets not forgetting the cultural heritage request new methods : theoretical and numerical tools to assess monitor and predict long-term performance of structures and components. New concepts to extend the life time of structures or increase their (bearing) capacity without service disruption, identification and measurement of a small number of significant parameters, combining performance prediction, monitoring and cost-efficient easy to maintain wireless sensors, new non destructive inspection techniques with no impact on traffic or supply, equipments with reduced installation time.

The cultural heritage should benefit from long-lasting intelligent wireless sensor networks, new NDT and monitoring technologies.

Practical simulation methods for the determination of load conditions, global and local damages as well as damage assessment are mentioned as an objective for 2030.

Finally, the construction sector must become attractive to young talented professionals. The smart technologies to be introduced may contribute making the sector more attractive than it is now.

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