Merging advanced sensing techniques and simulation tools for future structural health monitoring technologies

From smart materials to smart engineering structures.

We live in a digital world with ever-expanding connected systems. But we have yet to design smart and autonomous mechanical structures that can perform online control of their health, taking anticipated actions during service before downtime or failure occurs. This is a critical need in areas, such as energy transport, to achieve greater reliability and performance of the employed structures (aircrafts, wind turbines, bridges etc.). It would permit optimised maintenance and the capability to operate in degraded mode, managing the decrease of loading capabilities by adapting the operating plan.

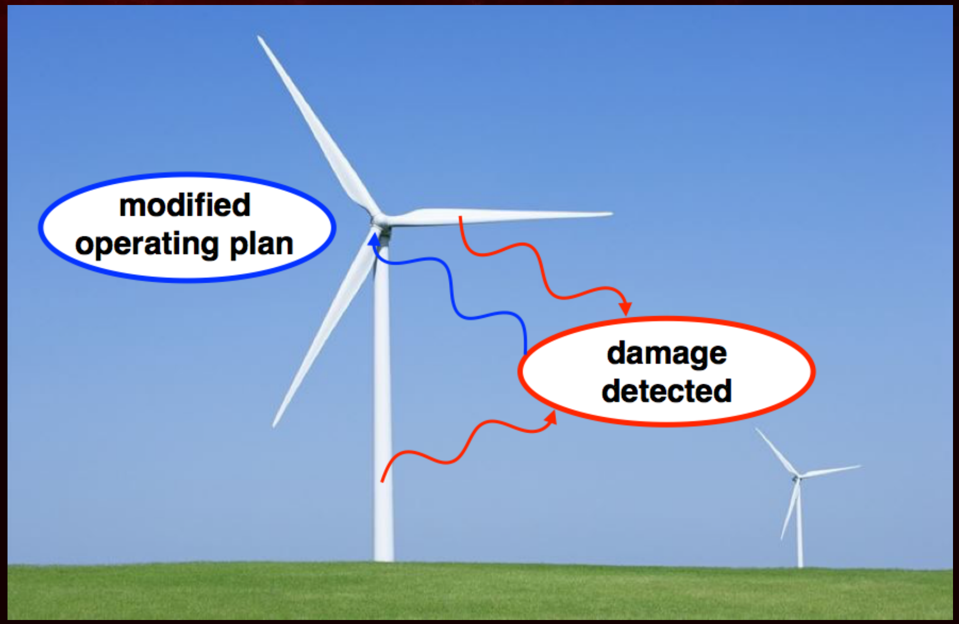

Figure 1: Monitoring of a wind turbine.

Tracking structural damage and predicting its evolution has been a perpetual engineering issue during the last decades. It was the topic of intensive research works, with both experimental and numerical advances. On the one hand, on-board sensing techniques with embedded micro-sensor arrays nowadays permit accurate in situ measurements on mechanical strain and thus provide very rich experimental information on the internal damage state of materials (Azam, 2014). In particular, the technology using standard optic fibres coupled with Rayleigh backscattering (Sanborn *et al.*, 2011) is very attractive as it delivers a real-time distributed characterisation of the strain field with unmatched spatial resolution (thousands of measurements per metre). Such a technology has already been employed in several applications and is increasingly envisioned by industrialists for structural health monitoring (SHM) (Di Sante, 2015).

On the other hand, sophisticated physics-based tools now permit the simulation of damage phenomena with high-fidelity and give a relevant virtual image of the material state. They involve predictive models with macro- up to micro-scale damage descriptions, with increasing complexity and computational cost (Lemaitre and Desmorat, 2005). They constitute a rich history of simulation-based engineering sciences, and they are now commonly used as numerical twins for design and optimisation. These computational models are classically fed and *a posteriori* compared with experimental data in order to ensure simulation reliability.

The scientific bottleneck for going from smart materials to smart structures is in the monitoring of large complex engineering systems. A shortcoming of data science alone is in the management and interpretation of sensor information with large, noisy data sets and predicting the structural behaviour involving localised multiscale and highly nonlinear damage phenomena. Moreover, from complex physics-based simulations alone, it is difficult to perform safe commands within a changing environment and with real-time requirements to be reactive and avoid instabilities in damage evolutions. As a matter of fact, high-fidelity simulations are very costly, requiring hours of parallel computing in practical applications, and they remain an imperfect representation of reality.

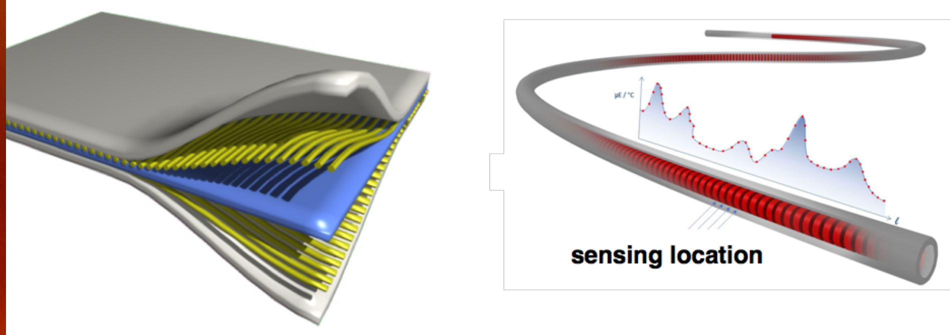

Figure 2: Distributed sensing in materials using optic fibres.

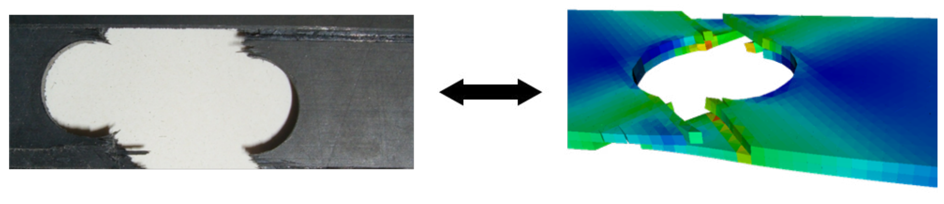

Figure 3: Virtual simulation-based representation of damage in composite materials.

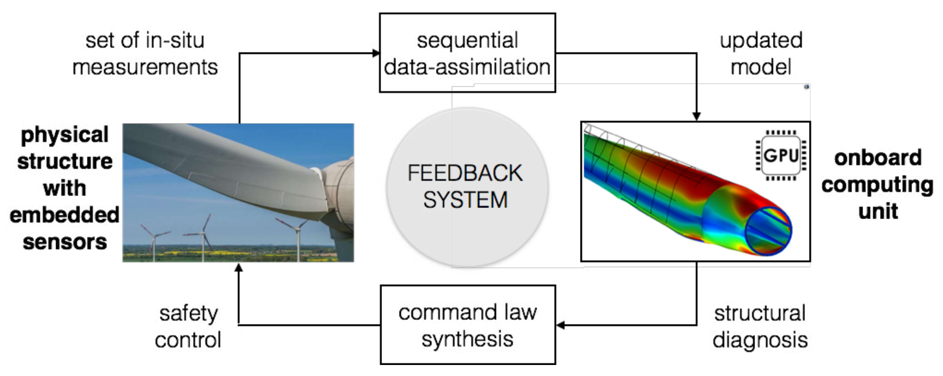

Figure 4: DDDAS concept applied to SHM on a wind turbine.

Designing a synergistic dialogue between the physical structure and its virtual twin

To cross the gap, the innovative concept of the project is a synergistic dialogue between advanced structural sensing (from embedded optic fibres) and command (from the structure actuators) on the one hand, and the most powerful modelling and simulation tools of computational mechanics on the other hand.

The dynamical connection between the mechanical structure and the on-board physics guided simulator is seen as a real-time feedback loop. It aims to provide benefit by making all knowledge available from rich data and high-fidelity simulation, and to exploit the best of each to perform early damage detection, precise diagnosis and to enable appropriate decision making.

The physics-based model is continuously updated and enriched from in situ observations which are assimilated on the fly. Damage diagnosis and predictive command are performed from the simulation to drive the system accordingly. This refers to the dynamic data-driven application systems (DDDAS) framework, which is a visionary paradigm in which a continuous exchange between simulations and in situ observations is implemented (Darema, 2004). It constitutes one of the most challenging applications of simulation-based engineering sciences.

Key numerical challenges

The DDDAS concept combining data and physics-based models is not new, but its practical implementation for damage monitoring remains limited to toy problems due to computationally intensive procedures. Consequently, the richness of data that is nowadays available on real-life structures is not exploited to its full extent for SHM.

Achieving a manageable feedback loop for large-scale structures, with highly nonlinear models, numerous data, and various uncertainty sources entails major research challenges to accommodate real-time, robustness, and portability issues (merely exploiting modern supercomputing facilities, with limited accessibility, is not an option).

The objective of the project is to develop, implement, and test a light, digital platform that combines all these features. Thus, DREAM-ON addresses key challenges by designing innovative and effective approaches to build the numerical core (central system) of DDDAS, from sensing to command.

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An original cross-disciplinary methodology will be followed. It will mobilise various skills embracing experimental mechanics, data science, mathematical modelling and simulation, applied mathematics, and computer science. The three main topics it will focus on are:

- effective and physics-guided data assimilation by designing a modified version of Kalman filtering with specific regularisation from the thermodynamics of continuum media, in order to infer noisy sequential measurement streams and recursively recover material state and model parameters.
- multiscale adaptive modelling (with local higher accuracy in regions where damage occurs) in order to strike the right trade-off between detailed damage representation and computational efficiency, so that computing resources are managed at best.
- certified command synthesis on evolving systems, by means of variants of model predictive control (MPC) with constraints, to limit damage effects and make the structure remain in a safety regime while in operation.

The methodology will use AI learning tools coupled with a sharp a priori knowledge on the physics fundamentals and specific features of studied damage phenomena to complement and enrich pre-existing models from data efficiently and thus make the virtual representation and resulting predictions closer to reality. This data-based correction of model ignorance refers to the recent concepts of physics-constrained AI and hybrid twins (Maday *et al.*, 2015; Hernandez *et al.*, 2021), in which a hybridisation between physics-based and phenomenological data-based models is implemented.

The whole numerical architecture will also involve reduced order modelling (ROM) which has been a major numerical achievement of the last decade, dramatically reducing CPU costs and memory resources when performing large and multi-query simulations. It is now a mature technique in computational science and engineering that enables real-time applications of SHM to be envisioned (Kapteyn *et al.*, 2021). Nevertheless, using such ROM at all stages of the DDDAS loop is far from sufficient, and the core of the project is to design and validate complementary unconventional approaches for computing, learning, and controlling, to fully reach the DDDAS objectives.

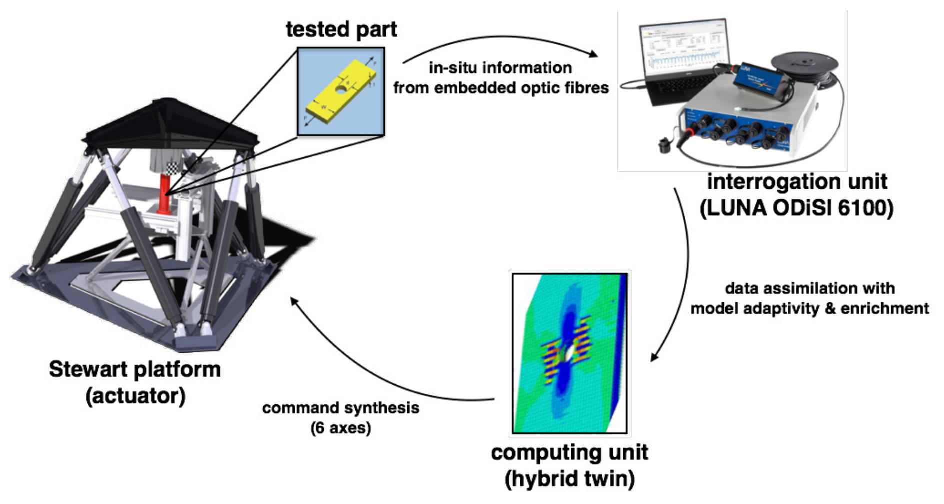

Figure 5: Proof-of-concept for the DREAM-ON project.

Validation on a proof-of-concept

The methodology will be developed with structures made of composite materials. These materials encompass complex damage phenomena occurring at different scales; even with small sizes, these may be precursors to increasing damage that degrades the overall structural performance.

The numerical strategy will be implemented and tested on a dedicated numerical platform, with unified, integrated architecture run by GPUs. Practical validation will take place via a representative and original lab experiment, seen as a proof-of-concept that will aim to preserve the integrity of a reduced-size composite structure under monitored mechanical loading. This experiment will involve the following two specific experimental facilities:

- a multichannel high-resolution optic fibre interrogator, based on the Rayleigh backscattering in the frequency domain (OFDR) technology, for on-the-fly distributed strain sensing (sub-millimetre gauge pitch, a maximal measurement rate of 250Hz)
- a Stewart platform (six-actuator parallel-kinematic hexapod) with high multiaxial load capacity to perform active structural command.

Economic and societal impacts

The project has the potential to generate a disruptive change and make the DDDAS dream come true for real-life mechanical structures. It is expected to lead to significant scientific and technological outcomes in all industrial activities where large critical engineering structures are employed and where damage tolerance is of paramount importance. It will force a breakthrough to move to smart structures with integrated sensing and predictive power interpretability from high-fidelity simulations. DREAM-ON will be a key enabler for next-generation SHM technologies with extended competitiveness and robustness. The knowledge gained throughout the project may also impact a variety of engineering fields, from manufacturing to biomedicine (with control of damage in biologic tissues during robot-assisted and image-guided surgeries). New opportunities will arise for the design of modern self-aware and smart-driven systems that adapt to evolving conditions (Lake *et al.*, 2017), thus answering the challenges of operational efficiency, sustainability and resilience with high-consequence decisions.

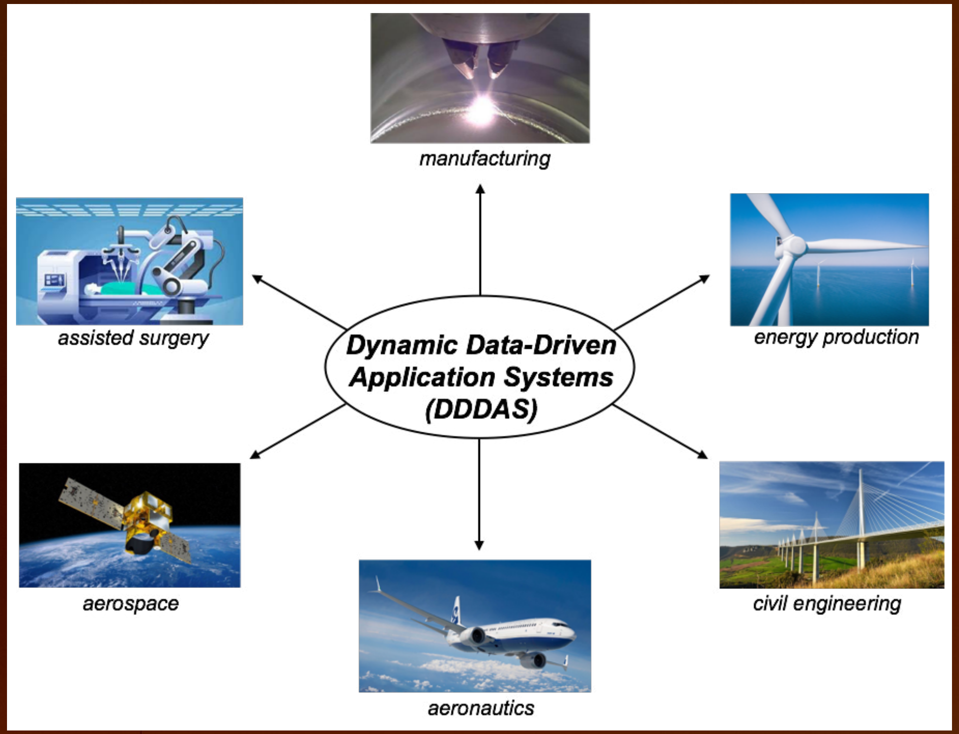

Figure 6: Potential structural applications of DDDAS.

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PROJECT NAME

DREAM_ON

PROJECT SUMMARY

Project DREAM-ON aims to design smart autonomous mechanics structures, able to perform online control of their health and take anticipated actions during service for increased reliability and performance. Its innovative concept is a synergistic, real-time, and robust dialogue between advanced sensing techniques and powerful simulation tools to make all knowledge on the physical system available and perform early damage detection, precise diagnosis, and safe decision making.

PROJECT LEAD

Ludovic Chamoin is a full professor in the mechanical engineering department at ENS Paris-Saclay. His research activities in computational mechanics are broad, with strong links with applied mathematics and industry. He is the head of a research team working on model certification and adaptivity, data assimilation, uncertainty quantification, and optimal control applied to engineering structures. Chamoin has published circa 80 papers in international journals, was an invited lecturer at the last World Congress in Computational Mechanics (WCCM-ECCOMAS 2020), and received awards including the John Argyris Award and the Robert J. Melosh medal. In 2019, he was selected as Junior member of the Institut Universitaire de France (IUF).

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