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1 Introduction

The Horizon 2020 Marie Skłodowska-Curie Actions Innovative Training Networks (H2020 MSCA ITN) program aims to foster excellence and innovation in research, while also promoting interdisciplinary collaboration and knowledge exchange. The project ENHAnCE, which stands for European training Network in intelligent prognostics and Health mAnagement in Composite structurEs, embodies these ideals and considers publishing as a key step for the advancement of knowledge, the recognition of researchers' contributions, and the progression of their academic careers.

In this deliverable, the collection of papers submitted to top journals and popular websites is provided. This collection represents a culmination of rigorous research, innovative thinking, and collaborative efforts undertaken by the Early Stage Researchers (ESRs), supported by supervisors, partners and collaborators. The papers that have been submitted to esteemed academic journals and prominent online platforms, with a diversity of topics covered, ranging from self-adaptive optimized maintenance policies to physics informed neural networks for prognostic or numerical simulation-aided particle filter-based damage prognosis using Lamb waves. Each paper represents a unique contribution to the advancement of knowledge within its domain, offering novel insights, methodologies, and perspectives that contribute to the broader academic discourse.

By disseminating the findings through both traditional academic channels and popular online platforms, we aim to maximize the impact and reach of our research. Through this multifaceted approach to dissemination, it is intended to engage with diverse audiences, including fellow researchers, policymakers, practitioners, and the general public, thereby fostering greater awareness, and understanding.

The papers included in this document are organized based on the main author, who Is an Early Stage Researcher (ESR), as well as by their respective topics. Additionally, they are distinguished by whether they have been submitted to journals or presented at conferences.

Papers submitted to journals undergo a rigorous peer-review process, where they are evaluated by experts in the field for their originality, significance, methodology, and contribution to the existing body of knowledge, being accessible to researchers worldwide.

On the other hand, papers presented at congresses or conferences are drawn in the form of conference proceedings. While they undergo some level of review by the conference organizers, the evaluation process is generally less extensive compared to journal submissions. Presenting at congresses provides researchers with an opportunity to share their findings with colleagues, receive

feedback, and engage in discussions with fellow scholars, practitioners, and policymakers. The papers submitted to journals are also extensively featured on their popular websites, ensuring wide accessibility and reaching a broad audience.

In conclusion, both means offer valuable opportunities for disseminating research findings and contributing to academic discourse. While journal publications become part of the academic record and undergo thorough scrutiny, conference presentations enable immediate dissemination of research results along with a valuable academic exchange.

At the time of composing this document, a total of 35 articles have been gathered, contributed by the ESRs members of this project. These articles cover a wide array of topics and reflect the collaborative endeavours of our research team. In the subsequent sections of this document, summaries for each article will be provided, outlining their significant findings, and how they contribute to the project's goals.

At this standpoint, it is important to note that the publication policy established by the Supervisory Board, by proposition of the Coordinator Prof. Manuel Chiachío, is to publish only in top and recognized journals, and following the highest standards of research integrity and assessment, as per the San Francisco Declaration on Research Assessment, along with the Open Science requirements.

2 Articles submitted to journals

Peer-reviewed publication ensures that research undergoes rigorous scrutiny by experts in the field, validating its credibility, accuracy, and significance. This process helps maintain the quality and integrity of academic work.

2.1 ESR 2 Aravind Balaji

RESEARCH TOPIC: Virtual Laboratory for Modelling and Optimisation of Manufacturing of Composites Structures with embedded structural health monitoring systems.

HOST INSTITUTION: Centre National de Recherches Aérospatiales (Cenaero)

ARTICLES SUBMITTED TO JOURNALS:

2.1.1 Prediction of shape distortions in thermosetting composite parts using neural network interfaced visco-elastic constitutive model

AUTHORS: Balaji A., Sbarufatti C., Dumas D., Parmentier P., Pierard O., Cadini, F.

JOURNAL: Journal of Composite Materials, 00219983241235855. (2024)

LINK: https://journals.sagepub.com/doi/full/10.1177/00219983241235855

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 859957.

SUMMARY OF MAIN OUTCOMES: A non-parametric neural network model has been developed using characterization tests under various thermal loading conditions. The neural network-enhanced constitutive model outperforms the standard cure kinetics-interfaced constitutive model in accurately predicting distortions for the Z-shaped case study.

SUMMARY AND CONCLUSIONS: Process-induced defects and residual stresses are inevitable during the manufacturing process due to the mismatch of free volumetric free strains resulting from thermal expansion and chemical shrinkage. The mechanism behind development of defects occurs at different mechanical levels. When assessing the residual stress field, the primary interest lies in the evaluation of distortions and performance-related attributes such as micro-cracks and reduced mechanical properties. Such defects could potentially be mitigated by adopting an optimal temperature cycle, which necessitates numerous iterative numerical analyses before the manufacturing process.

A linear viscoelastic constitutive model, based on the path dependence of cure state variables, has been implemented for numerical analysis on thermosetting composite parts subjected to autoclave conditions. Moreover, the numerical modelling of residual stress relies on the homogenized mechanical and thermo-chemo properties of the resin and fibre, depending on the curing behaviour. Therefore, accurately capturing the transitions between the viscous, rubbery, and glassy states is crucial. These cure behaviour and state transitions, which depend on cure state variables, are defined using cure-kinetics and DiBenedetto's models, involving numerous constants. The modelling of such a cure-kinetics model requires extensive knowledge of various Arrhenius models and prior information about model parameters. However, such parametric cure models have been observed to be unable to accurately capture the non-linear relationships between the cure state variables and the thermal loading condition variables. These complex relationships are captured in this study by using a non-parametric neural network model that, however, requires extensive training. The study provides insights into the influence of thermal loading rates (below 3°C/min) on the evolution of cure state parameters for carbon/epoxy prepreg AS4/8552. The neural network model is integrated with the constitutive model to enable accurate predictions of process-induced distortions in the case study of a Z-shaped thermoset part. Several significant conclusions and remarks from the study are as follows:

• It has been observed that the cure state variables are dependent on process conditions, specifically the thermal loading rates.

• To capture the non-linear relationship between cure kinetics and process condition variables, a non-parametric neural network model is implemented using DSC characterization tests conducted under various thermal loading conditions. Such a model has been found to be particularly useful when dealing with thick thermoset parts that are subject to temperature gradients.

• When tested with new data for the carbon/epoxy prepreg AS4/8552, the neural network model provides more accurate state transitions between the viscous, rubbery, and glassy states compared to the conventional diffusion cure-kinetics and DiBenedetto's models under below 3°C/min.

• For the case study of the Z-shaped thermosetting part, the proposed approach predicts process-induced distortions in the form of spring-in angles that correlate more closely with experimental measures obtained from laser scans.

By training and implementing the neural network model, the expenses tied to comprehensive characterizations under diverse boundary conditions for thermosetting composite materials can be circumvented, allowing the attainment of desired intermittent temperature rates and maximum curing temperatures. The trained networks can subsequently be integrated with the constitutive models to forecast process-induced defects. This approach furnishes an initial estimation of defects and streamlines the optimization of temperature profiles to mitigate risks and enhance manufacturing quality.

2.2 ESR 3 Amond Sarr Allouko

RESEARCH TOPIC: Computing Platform Based on Novel High-Order Numerical Methods for Smart FRP Composite Structures with Embedded AU-SHM sensors.

HOST INSTITUTION: Atomic Energy and Alternative Energies Commission - Laboratory for Integration of Systems and Technologie (CEA List)

ARTICLES SUBMITTED TO JOURNALS:

2.2.1 Optimal computation of integrals in the Half-Space Matching method for modal simulation of SHM/NDE in 3D elastic plate

AUTHORS: A. Allouko, A.-S. Bonnet-Ben Dhia, A. Lh´emery, V. Baronian

JOURNAL: The Journal of Physics: Conference Series. (2024)

LINK: Pending of Publication

SUMMARY OF MAIN OUTCOMES: The Half-Space Matching (HSM) method has been established for the development of a model that hybridizes local finite element (FE) computations for GW scattering by a flaw. Integral formulae appear in the HSM method. A method is proposed to reduce by a factor of 10 the time to get a good accuracy of these integrals.

2.3 ESR 4 Tasdeeq Sofi

RESEARCH TOPIC: Novel procedure for designing, manufacturing and assembling smart composite wind turbine blades with embedded AU-SHM sensors.

HOST INSTITUTION: Foundation for Research, Development and Application of Composite Materials (FIDAMC)

ARTICLES SUBMITTED TO JOURNALS:

2.3.1 An Efficient Procedure for Bonding Piezoelectric Transducers to Thermoplastic Composite Structures for SHM Application and Its Durability in Aeronautical Environmental Conditions

AUTHORS: Sofi, T., Gude, M.R., Wierach, P., Martin, I., Lorenzo, E.

JOURNAL: Sensors 23, 4784. (2023)

LINK: https://www.mdpi.com/1424-8220/23/10/4784

SUMMARY OF MAIN OUTCOMES: The article introduces a novel approach to bonding sensors to aircraft structures using thermoplastic films, offering an easily installable, reparable, and more reliable method. It highlights the limitations of the current method, which involves bonding transducers to composite structures using epoxy adhesives. These shortcomings include difficulties in reparability, weldability, longer curing cycles, and shorter shelf life. Through testing in standard aeronautical environmental conditions, the proposed method demonstrates superior performance compared to bonding with epoxy adhesives.

SUMMARY AND CONCLUSION: A new efficient method of integrating PCTs to TP composite structures was proposed by using TPFs rather than epoxy adhesives. The TPFs were chosen based on certain criteria and characterized with standard tests. The bonding ability of the chosen TPFs was checked by EMI and lamb-wave measurements. The reparability, which is one of the main advantages of TP adhesives, was demonstrated through a very simple setup. To demonstrate the durability of the proposed bonding method in aeronautical applications, the AUCTs were bonded to TP coupons through the chosen TPFs and put through standard AOEC tests. It was shown that the changes produced in the AUCT characteristics during the AOEC tests were significantly smaller than the changes caused due to AUCT defects. Thus, no significant degradation occurred in the AUCT during the AOEC tests.

The most critical AOEC tests for all the adhesive films whether the epoxy reference film or the chosen TPFs were the fluid susceptibility tests of Kerosene and Acetone, which introduced the maximum changes in the SS characteristics. However, such scenarios of AUCTs getting immersed in fluids such as Kerosene and Acetone are less likely to occur in real-life applications. Nevertheless, any changes that can occur in the AUCT characteristics because of these conditions should be taken into account in the SHM system. Taking these changes into account can also help the SHM designer to set a threshold to distinguish between the changes in the guided wave signal because of the sensor and structure in order to avoid any false alarms.

After comparing the performance of the bonded AUCTs in the AOEC tests, it was seen that some TPFs outperformed the reference epoxy film, while other TPFs had a similar performance, like

that of the reference epoxy film. Thus, the proposed method of bonding the AUCTs is more efficient, easy, and reliable than the current state-of-the-art method of bonding AUCTs with epoxy glue.

However, this study is limited to a particular type of epoxy film adhesive and special state-of-the-art PCT transducers. Although they represent the state-of-the-art, it may be possible that other types of epoxy adhesives and PCTs may have better or worse performance in the AOEC tests performed in this study. This study could be extended to other types of adhesives to establish if the TPFs have better performance with respect to other adhesives or not. In addition to EMI methodology employed in this study to measure the changes in the AUCT characteristics, other methods, such as changes in the guided wave signals and out-of-plane velocity, could be performed, which can give more insights into the changes that can occur in the adhesive layer and the AUCT characteristics during the AOEC tests. In the current study, the AUCT have been bonded to the composite specimen by oven heating and vacuum bagging. This process can be time-consuming and may require heating the entire structure, which can cause thermal degradation to the structure. To overcome these drawbacks, an easier, faster, and economic method of bonding AUCTs to TP composite structure using local induction heating is currently being investigated by the authors. Furthermore, it is very important to study the mechanical performance of the selected TPFs as compared to the epoxy adhesives used to bond the AUCTs. Therefore, the mechanical performance of the AUCTs bonded with the TPFs with oven and induction heating will be studied in great detail through different mechanical tests, such as tensile-tensile fatigue and static and cyclic flexural tests, and compared with that of the epoxy adhesives.

2.4 ESR 5 Morteza Moradi

RESEARCH TOPIC: Prognostic signatures based on data-fusion techniques from Lamb-wave and acoustic emission in real-world FRP laminates subjected to random fatigue damage.

HOST INSTITUTION: Delft University of Technology (TU Delft)

ARTICLES SUBMITTED TO JOURNALS:

2.4.1 Intelligent health indicator construction for prognostics of composite structures utilizing a semi-supervised deep neural network and SHM data.

AUTHORS: Moradi, M., Broer, A., Chiachío, J., Benedictus, R., Loutas, T. H., & Zarouchas, D.

JOURNAL: Engineering Applications of Artificial Intelligence, 117, 105502. (2023).

LINK: https://www.sciencedirect.com/science/article/pii/S0952197622004924

SUMMARY OF MAIN OUTCOMES: The research focuses on the development of an intelligent Health Index (HI) utilizing acoustic emission data obtained from composite panels. It employs a semi-supervised learning approach, implicitly integrating prognostic criteria into the model construction process. Through the application of a Bayesian optimization algorithm, the study identifies optimal network architectures for enhanced performance. Results indicate a significant 77.3 percent improvement in HI quality based on prognostic criteria. Additionally, the study verifies the approach's generalization capabilities through leave-one-out cross-validation. Overall, the research demonstrates promising advancements in HI construction using acoustic emission data and semi-supervised learning techniques.

SUMMARY AND CONCLUSION: A roadmap to construct an intelligent HI suitable for usage in prognostic models was proposed in the presented work. Following feature extraction with the purpose of dimensional reduction from the time and frequency domains of acoustic emission data captured during monitoring of single-stiffener composite panels, a feature fusion (FF) step based on semi-supervised learning was performed to ensure that the obtained HI after FF complies with the prognostic criteria. The quality of the constructed HI is measured and confirmed using these criteria, which include monotonicity, trendability, and prognosability. As a result, a semi-supervised deep neural network (SSDNN) was suggested to implicitly induce a multi-layer LSTM network that meets these criteria, as well as overcome the lack of labeled data and exploit unlabeled data to train models. Ten top models were selected from a Bayesian optimization algorithm applied to a holdout validation (ten CSs as training, one as validation, and one as a test), and they were then evaluated using the leave-one-out cross-validation (LOOCV) approach.

According to the holdout validation, the high Fitness score of 2.891 for HIs (maximum Fitness is 3) highlighted model 1's remarkable performance in constructing HIs based on prognostic criteria, which is 77.3% higher than the best feature (1.6303). Indeed, the proposed scenario's efficiency was reflected in this Fitness gain. Moreover, according to LOOCV, the best generalized models 7, 8, and 5 with the average (ensemble) HIs achieved mean Fitness values of 2.786 ± 0.144, 2.747 ± 0.146, and 2.729 ± 0.199, respectively. For the first fold, the difference in deviation between the target, which is the ideal hypothetical HI, and the average produced HI was considerable (e.g., model 7 has a mean RMSE value of 0.296 ± 0.061). It is likely due to unfit training progress adjustments for this fold (e.g. validation check patience set to 6), highlighting the proposed DNN models' limitations, which can be addressed in future work focused at designing more generalized models and training progress for all folds. Nonetheless, the results showed that all CSs possessed patterns that were similar to some extent, resulting in a reasonable Fitness value (2.453 for model 7, indicating an 81.77% quality). While model

7 was unable to generate HIs that satisfied the first fold's targets (i.e., high RMSE), it was able to intelligently fuse the input features to yield an average HI that reflected the prognostic requirements (i.e., high Fitness). In other words, the model has figured out how to integrate and fuse the features to produce a HI with relatively the same pattern for all composite specimens, which can be utilized for more accurate and reliable prediction of EOL and decision-making. The prognostic criteria were implemented within the feature fusion and HI construction framework for this advancement rather than being used solely as a quality measurement tool for HI.

2.4.2 A Novel machine learning model to design historical-independent health indicators for composite structures.

AUTHORS: Moradi, M., Gul, F. C., & Zarouchas, D.

JOURNAL: Composites Part B: Engineering, 111328. (2024).

LINK: https://www.sciencedirect.com/science/article/pii/S1359836824001392

SUMMARY OF MAIN OUTCOMES: The proposed approach relies solely on current guided wave (GW) data, eliminating the need for historical information. It offers flexibility in accommodating various GW sensor configurations and setups. Validation studies conducted on T-single stiffener CFRP panels subjected to compression-fatigue loading and dogbone CFRP specimens under tension-fatigue loading demonstrate high performance, with success rates reaching up to 93% and 81%, respectively. Overall, the methodology showcases promising adaptability and effectiveness in structural health monitoring applications.

SUMMARY AND CONCLUSION: This study has introduced an innovative approach to constructing comprehensive health indicators (HIs) for composite structures, addressing the challenges posed by the stochastic nature of damage accumulation during operational conditions and the need for HIs independent of historical data. Leveraging the power of AI, we developed the Hilbert transform-convolutional neural network (HT-SSCNN) within a semi-supervised learning paradigm. The approach exclusively utilizes current guided wave (GW) data, eliminating the reliance on historical information. It flexibly accommodates different GW sensor numbers, networks, and setups. The results demonstrate the effectiveness and validity of the approach. To assess various combinations and ensure robustness, rigorous evaluations were conducted, considering different datasets under various conditions.

The findings indicate that certain frequencies, such as 150 kHz for the ReMAP dataset and 250 kHz for NASA Layup 1, consistently outperformed others, resulting in more stable and reliable HIs. The use of ensemble learning techniques, specifically WAE-Fitness, led to significant

improvements in HIs' performance. For the ReMAP dataset, the WAE-Fitness model, fusing all GW excitation frequencies, yielded the best fitness scores, with 93% accuracy considering all units and 89% given test units. While ReMAP experiments are more complex than the NASA ones, HIs with higher performance could be extracted from the ReMAP dataset than the NASA dataset, which can be attributed to the availability of one more training specimen and a greater number of time steps for GW inspections. Additionally, ReMAP structures were monitored using a more intertwined GW sensory network, which provided a wealth of data for model training. The produced HIs exhibit desirable properties for RUL prediction. They are monotonic, prognostable, and exhibit correlated trends, which are essential characteristics for accurate predictions in PHM. The incremental steps observed in the HIs may potentially correspond to distinct damage states, which can be used to inform future state-based RUL prediction models. In conclusion, our approach offers a promising solution to the challenging task of constructing reliable and historical-independent HIs for composite structures. By combining AI with signal processing algorithms, we achieved a high level of performance and demonstrated the applicability of our method across different datasets. This research opens up new possibilities for enhanced health monitoring and predictive maintenance of composites.

2.5 ESR 6 Tianzhi Li

RESEARCH TOPIC: Development of super-fast Bayesian algorithms for real-time prognostics in composite structures using structural health monitoring.

HOST INSTITUTION: Politecnico di Milano (POLIMI)

ARTICLES SUBMITTED TO JOURNALS:

2.5.1 Particle filter-based hybrid damage prognosis considering measurement bias.

AUTHORS: Li, T., Sbarufatti, C., Cadini, F., Chen, J., & Yuan, S.

JOURNAL: Structural Control and Health Monitoring, 29(4), e2914. (2022).

LINK: https://onlinelibrary.wiley.com/doi/full/10.1002/stc.2914

SUMMARY OF MAIN OUTCOMES: This paper proposed a new bias-based prognostic model that can take measurement uncertainties into consideration, which has been demonstrated by fatigue crack prognostic studies.

SUMMARY AND CONCLUSION: The bias between the sensor observation and its prediction by a measurement equation is unavoidable in hybrid prognostic investigations, leading to inaccurate state and parameter estimations and prognostic results. Inspired by sensor fault diagnosis and hybrid damage prognosis, this paper has proposed a new hybrid state space model that includes a bias

parameter in the prognostic model for estimation. The experimental study, where an aluminium lug structure is subject to fatigue cracking and monitored by ultrasonic Lamb waves, has proven that the new model can provide accurate estimation and prognostic results provided that the bias is correctly estimated. Furthermore, the estimation and prognostic performances of the new approach have been shown to be noticeably more robust than those of the traditional model in the presence of an increasing bias. The slight performance reduction by increasing the bias level might not be avoided even in the newly proposed approach but can be alleviated by combining different features for damage quantification or by implementing an efficient state estimation technique for time-varying parameters.

The approach remains valid for more complex scenarios, although the acquisition of sufficient experimental or in-field data during the entire run-to-failure process might be infeasible, due to unconceivable costs. Thus, one may resort to simulated data, e.g. from a finite element model, for the definition of the measurement model and the process equation, surely affected by bias, thus justifying additional effort by the authors in present and future research. Moreover, with tens or hundreds of sensors installed on large structures, the measurement equation will become high-dimensional. Although most of the measurements will be unaffected by damage, due to its localized nature, this may lead to an inaccurate and time-consuming prognosis. Online selection of the most appropriate combination of observations is another promising field of research in this framework.

2.5.2 Numerical simulation-aided particle filter-based damage prognosis using Lamb waves.

AUTHORS: Li, T., Lomazzi, L., Cadini, F., Sbarufatti, C., Chen, J., Yuan, S.

JOURNAL: Mechanical Systems and Signal Processing, 178, 109326. (2022).

LINK: https://www.sciencedirect.com/science/article/pii/S0888327022004630

SUMMARY OF MAIN OUTCOMES: By combining numerical simulation and bias-based prognostic model, this paper has proposed a novel Lamb wave-based prognostic framework.

SUMMARY AND CONCLUSION: Lamb wave-based damage prognosis methods typically require a data-driven measurement equation to describe the relationship between the damage state and some properly chosen damage-sensitive features of Lamb waves. The formulation of such a model generally requires sufficiently experimental or in-field datasets collected during the run-to-failure process, which, however, may not be available due to some causes like the high costs.

By combining a numerical simulation-aided damage quantification method with a damage prognosis framework accounting for the unavoidable measurement bias, this work has proposed a new particle filter-based damage prognosis framework, which only requires numerically simulated Lamb waves for building the measurement equation. The proposed framework has three advantages, i.e.,

- The costs and efforts in conducting run-to-failure tests and collecting experimental or in-field data for model formulation can be avoided.
- The numerical database developed in this work only consists of nine Lamb wave propagation simulations, each of which requires a few computation efforts, i.e., about four minutes on an AMD Ryzen 9 3950X 16-Core Processor.
- The proposed method is robust, as validated by the results from the five specimens because it takes the uncertainties from both the damage evolution and measurement models into account by online updating their parameters.

In a more realistic application scenario, where tens of or hundreds of sensors are installed for monitoring, the measurement vector in this method can be high-dimensional and most of the measurements far away from the damage can be damage-insensitive, which should possibly lead to an inaccurate and time-consuming prognosis. In order to deal with this problem, one may refer to a proper measurement partitioning strategy by online selecting limited-amount damage-sensitive measurements for estimation.

2.5.3 Particle filter-based delamination shape prediction in composites subjected to fatigue loading.

AUTHORS: Li, T., Cadini, F., Chiachío, M., Chiachío, J., Sbarufatti, C.

JOURNAL: Structural Health Monitoring, 22(3), 1844-1862. (2023)

LINK: https://journals.sagepub.com/doi/abs/10.1177/14759217221116041?journalCode=shma

SUMMARY OF MAIN OUTCOMES: This paper has elaborated that the delamination shape in composites can be predicted and then proposed a new delamination shape prediction method.

SUMMARY AND CONCLUSION: This paper has developed a novel PF-based delamination shape prediction method for composites by taking the delamination shape as a damage state for damage prognosis. By artificially defining a number of CLs to discretize the delamination contour, the shape prediction problem can be simplified into the predictions of these CLs, whose efficiency has been demonstrated with reference to experimental tests of fatigue delamination growth in composite panels with ultrasonics C-scan monitoring during the entire run-to-failure process. This method has been proven robust over different specimens, as it can consider the uncertainties of damage evolution by online updating the CL model parameters.

To move toward a more practical application for delamination shape prediction, one may consider four potential development paths for this research.

Sufficient experimental or in-field delamination images during the run-to-failure process are required in this study to train the initial ranges in PF, which, however, may not always be feasible due to unconceivable costs. Thus, one may resort to simulated data, for example, from a finite element model, for the definition of the initial ranges. The uncertainties arising from the difference between the numerical and experimental delamination growths can then be automatically taken care of by the adaptation capabilities of PF:

- In case even numerically generated data are not available, one may, for example, fit the model parameters by assuming no delamination growth during the fatigue test and then create sufficiently wide initial ranges for the parameters in PF implementation, probably at the expense of slower convergence and larger uncertainty intervals at early steps, thus calling for some PF modifications for fast convergence.
- Provided that the adaptability of a quadratic function may not be sufficient for other practical cases with too large uncertainties, involving, for example, more complex delamination shapes, delamination depth, etc., a more sophisticated surrogate model like Gaussian process or neural network could be implemented for building a more detailed damage evolution model.
- Given the difficulty of the online implementation of the ultrasonic C-scan monitoring system, an online measurement system, for example, guided wave, can be adopted for inferring the delamination shapes through a data-driven function mapping between the shape and measurements, finally yielding an online damage prognosis framework for industrial application.

Finally, the general idea discussed in this work, that is, the simplification of a two-dimensional prediction problem into the predictions of some CPs, can potentially contribute to the other applications, for example, for the deformation estimate during the service life of a structure, which is left for the interested readers.

2.5.4 Particle filter-based damage prognosis by online feature fusion and selection.

AUTHORS: Li, T., Chen, J., Yuan, S., Cadini, F., Sbarufatti, C.

JOURNAL: Mechanical Systems and Signal Processing, 203, 110713. (2023).

LINK: https://www.sciencedirect.com/science/article/pii/S0888327023006210

SUMMARY OF MAIN OUTCOMES: Given the usage of the sastistical feature can have a significant effect on prognostic performance, this paper has proposed a new online feature fusion and selection method within a particle filter-based prognostic framework.

SUMMARY AND CONCLUSION: Damage prognosis methods typically require a data-driven measurement equation to describe the relationship between the damage state and some properly

chosen damage-sensitive statistical features. As the best feature can vary for different specimens, or even, at different time steps for the same specimen, the selection of such a feature can hardly be a trivial task but has received little attention in current practices. By combining a novel online feature fusion and selection scheme with multiple prognostic models considering measurement bias, this work has proposed a new particle filter-based damage prognosis framework, where, at each step, the feature with the smallest estimated bias is taken as the best feature providing the best estimates at that step. The results of the new method have been compared with the traditional approach, where the prognostic model resorting to one feature has been processed through one PF for damage quantification and RUL prediction. The traditional method has shown performance dependence on the feature choice. The smaller bias one feature has, the better performance it can provide, as a smaller bias can be more accurately estimated, having less effect on the estimat
ion of the crack length. Any feature can be the best feature at specific steps, and the proposed method maximizes the use of the best features, thus yielding more accurate estimation and prognostic performances. To move towards a more practical and robust application, one may consider three potential paths, from the perspectives of degradation modeling, feature fusion, and feature selection:

- This method exclusively relies on Paris's law for degradation modeling, without considering uncertainties stemming from factors such as the calculation of stress intensity factor and fatigue cycle counting. Consequently, the prognostic performance can be improved by incorporating additional uncertainties into the prognostic model. Moreover, one can explore the fusion of multiple physics-based and data-driven models to create a group of better-distributed damage state samples as prior and then to enhance the estimation and prognostic performance.
- This method is only validated in a case study where some statistical features are extracted from Lamb wave signals, specifically by the same piezoelectric transducer. However, practical monitoring scenarios usually have multiple transducers and different types of sensors, like strain gauges and accelerometers, installed, resulting in different statistical and physics-related features. Due to the potentially significant variations in sensitivity and scale (or bias level) among these features, feature fusion remains a significant challenge.
- This method only resorts to the bias parameter for selecting the best feature at each step. The performance of PF-based estimation can be evaluated by other coefficients like the effective sample size, which could be also exploited for selecting the best feature. Furthermore, rather than always resorting to the particles from the best feature, different groups of particles can be weighted by the above coefficients and then applied to prior calculation, improving the particle diversity and possibly yielding a more robust prognostic performance.

2.5.5 Multiple local particle filter for high-dimensional system identification.

AUTHORS: Li, T., Sbarufatti, C., Cadini, F.

JOURNAL: Mechanical Systems and Signal Processing, 209, 111060. (2024).

LINK: https://www.sciencedirect.com/science/article/pii/S0888327023009688

SUMMARY OF MAIN OUTCOMES: This paper has proposed a new particle filter method that can offer the possibility of beating the curse of dimensionality, which has been validated by the numerical simulation of bounce wen frame structure and the experimental study of fatigue crack prognostic.

SUMMARY AND CONCLUSION: The application of particle filter in a high-dimensional system is limited due to the curse of dimensionality. By combining multiple particle filter (MPF) and the decay of correlations property, this paper has developed a novel multiple local particle filter (MLPF) for system identification. One state vector is partitioned into several state subgroups, each containing the components from one DOF or one control length (CL) and then estimated by one PF. The superior performances of the MLPF over the MPF and the PF with respect to computation effort and estimation accuracy have been proved by the identification results of the toy example, the numerical twenty-story Bouc-Wen frame structure under the ground motion, and the experimental fatigue delamination shape prediction in composites.

The number of particles required by the PF will exponentially increase with the state dimension, while the number of particles required by the MPF or the MLPF will remain relatively stable. This proves the abilities of the MPF and the MLPF in alleviating the curse of dimensionality. the MLPF can provide similarly accurate estimations as the MPF under the same number of particles but requires less computation time due to fewer components involved in the likelihood. This advantage of the MLPF over the MPF will be even more apparent in a higher-dimensional system, where the number of components within the likelihood of the MPF will increase with a higher state dimension, while the number of components for the MLPF may not increase as much.

For the system identification of the twenty-story frame structure, it has been found that the stiffness of the story closer to the ground motion shows faster convergence, possibly due to its higher contribution to the likelihood calculation at the initial steps. Furthermore, PF algorithms can work with partial acceleration measurements but provide less accurate estimates. Finally, the generalizability of MLPF to different SHM applications has been validated by the delamination shape prediction in composites, where the future shape can be accurately predicted by the MLPF estimates.

The structures used in this study has been found to be simple, thus their state partitioning processes are straightforward, e.g., the state components from one DOF or control length. However,

this may not be as simple for the other SHM applications, especially those tailored for complex and 3D structures. To address this challenge, it is recommended that a sensitivity analysis should be conducted to determine the appropriate state partitioning and the required local vectors. Alternatively, an adaptive state partitioning approach could be developed to more fully explore the potential of this strategy for high-dimensional problems. By taking these steps, researchers can better tailor their SHM models to specific applications and ensure the most effective use of available data. Moreover, the proposed MLPF usually requires a sufficient number of measurements, which may not always be possible and still calls for an advanced system identification method with a limited number of measurements.

2.5.6 Particle filter-based fatigue damage prognosis by fusing multiple degradation models.

AUTHORS: Li, T., Chen, J., Yuan, S., Zarouchas, D., Sbarufatti, C., Cadini, F.

JOURNAL: Structural Health Monitoring, 14759217231216697. (2024).

LINK:

https://journals.sagepub.com/doi/full/10.1177/14759217231216697?casa_token=BgauJcW9dwAAAAAA%3AfHlJ1WNbWAQXGGNrC4s4ywixK_6Pm2r0c7HjPj24u9htirKh1vuz8kh6CE449n650QYe088exMPJ-Q

SUMMARY OF MAIN OUTCOMES: Given the usage of the degradation model can have a significant effect on prognostic performance, this paper has proposed a new online model fusion method within a particle filter-based prognostic framework.

SUMMARY AND CONCLUSION: Damage prognosis methods typically require a properly selected degradation model describing the damage growth with time or load cycle steps. To provide a more robust prognostic performance, this work has proposed a PF-based damage prognosis framework by fusing multiple degradation models.

The results of the traditional and new methods can lead to the following conclusions. When using the traditional method of relying on one degradation model, it is important to note that the best degradation model can differ among the five specimens and also vary depending on the performance metrics used. Simply combining the estimates from multiple models does not enhance the accuracies of crack length quantification and RUL prediction. In all of the five specimens evaluated, the new method, leveraging either the crossover or mutation operator, consistently outperforms the simple mixture mentioned above, attesting to its robustness.

Based on the results presented in this paper, it can be concluded that the proposed method offers a promising alternative to the traditional approach. While the proposed method may not always

result in superior performance compared to the best model-based traditional approach, it addresses the uncertainty involved in determining the most effective model in advance. Furthermore, the proposed method provides a more comprehensive evaluation of the degradation behavior by considering multiple models, which can enhance the accuracy of damage quantification and RUL prediction.

In a more practical application scenario where tens of or hundreds of available degradation models are available, some of those models may consistently provide inaccurate crack length quantification and RUL prediction results, thereby compromising the performance of the proposed method if such models are included. Consequently, it is necessary to develop an offline or online scheme to select a list of "good" degradation models or "good" samples. Moreover, the proposed method requires all the prognostic models to share specific state components like crack length, which may not always be possible, especially considering that some data-driven models only include some sort of data-driven HI. A necessary extension has to be made in the case of no shared state component.

Finally, it should be noted that the proposed approach requires the use of multiple PFs; thus, its computation time will linearly increase with the number of models (or PFs) used. However, this issue can be addressed by developing computationally efficient PFs, which will enable the use of more models without significantly increasing computation time and enhance the practical applicability of the proposed method.

2.6 ESR 7 Javier Contreras

RESEARCH TOPIC: Development of a System-Level Post-Prognostics Reasoner for FRP turbine blades using on-board SHM.

HOST INSTITUTION: University of Strahclyde, Glasgow, U.K.

ARTICLES SUBMITTED TO JOURNALS:

2.6.1 A cross-sectoral review of the current and potential maintenance strategies for composite structures.

AUTHORS: Contreras Lopez, J., Chiachío, J., Saleh, A., Chiachío, M., Kolios, A.

JOURNAL: SN Applied Sciences 4, 180. (2022)

LINK: https://link.springer.com/article/10.1007/s42452-022-05063-3

SUMMARY OF MAIN OUTCOMES: A review of the current state of O&M for safety-critical structures. Limitations in the use of composites and advanced maintenance methods in 4 different sectors (Civil, Aerospace, Wind and Naval) are derived.

SUMMARY AND CONCLUSION: The use of FRP composites in thin-walled structures for safety-critical applications has seen a notable rise over the last few decades, especially in the aerospace and wind industries with evidence of reliability, durability, life cycle cost reduction and sustainability. Other industries such as the civil and naval have not seen such a rampant increase so far presumably due to the uncertainty about the long-term performance, the lack of technological demonstrators, and the absence of codes and standards.To overcome this, the development of policies and codes regulating the design with composites along with a cross-sectoral knowledge transfer among industries could be the levers that unlock a greater use of these high-efficiency materials. Moreover, while still relatively immature for industrial application, converting composite structures into cyber-physical structures seems promising to promote the transition into predictive and optimised inspection and maintenance strategies and overcome the long-term performance uncertainty of FRP structures.

2.6.2 Risk-based maintenance strategy selection for wind turbine composite blades.

AUTHORS: Lopez, J. C., Kolios, A.

JOURNAL: Energy Reports, 8, 5541-5561. (2022).

LINK: https://www.sciencedirect.com/science/article/pii/S2352484722007922

SUMMARY OF MAIN OUTCOMES: A criticality ranking of the different failure modes of a wind turbine blade including a framework to select maintenance strategies for these. A review of the suitability of SHM for the failure modes identified is also provided.

SUMMARY AND CONCLUSION: In this study, a risk-based maintenance strategy selection for wind turbine composite blades was presented. First, the failure modes of the wind turbine blade were identified by means of an FMEA considering their likelihood of occurrence and the severity to determine their criticality. Later, the feasibility of monitoring the identified failure modes was explored in the literature. Finally, a maintenance decision tree was presented and applied to determine the preferred maintenance strategy of the prioritized failure modes providing a systematic way of choosing maintenance strategies for the critical failure modes of the blade.

The FMEA of a wind turbine blade identified the leading edge erosion, root-hub connection damage, spar caps and web damage, lightning strike damage, and the debonding of leading and trailing edges to be the most critical failure modes of the blade. This study has shown that detecting and/or monitoring these failure modes can be feasible as shown by the literature. Notwithstanding, the optimal placement of sensors, the tuning of inspection intervals and dealing with all the information obtained to take operation and maintenance decisions are non-trivial problems to be solved to unleash cost reductions for wind energy production.

2.6.3 A wind turbine blade leading edge rain erosion computational framework.

AUTHORS: López, J. C., Kolios, A., Wang, L., Chiachio, M.

JOURNAL: Renewable Energy, 203, 131-141. (2023).

LINK: https://www.sciencedirect.com/science/article/pii/S0960148122018353

SUMMARY OF MAIN OUTCOMES: A computational framework to evaluate wind tubine blade leading edge erosion effect on annual energy production and quantify the effect of weather uncertainty. AEP reduction is estimated to be in the range 1.25-1.75% for the case study.

SUMMARY AND CONCLUSION: An efficient leading edge erosion framework for AEP degradation erosion estimation has been presented and illustrated through a case study. The presented framework requires the aerodynamic curves of the pristine and eroded airfoils of, approximately, the outermost third of the blade (obtained through wind-tunnel tests or CFD simulations), weather (rain and wind) data of the site of study (based on on-site observations or other sources such as ERA5 reanalysis data), and erosion protection coating survivability data (based on erosion tests such as whirling arm tests). Based on this and assuming linear damage accumulation of the rain impingement model and a BEM model, the erosion and AEP degradation throughout time can be estimated. Alternatively, the aerodynamic performance of the blade can be obtained by considering 3D CFD simulations. Physical testing of weathered sections of the blade can improve the accuracy of the evaluation of the aerodynamic performance of eroded airfoils.

The case study using the 5 MW NREL wind turbine located in the location of FINO1 weather station revealed the importance of designing an adequate LEP coating. For one of the LEP configurations, GS, the incubation period was not consumed, and no relevant AEP losses are expected. For the other configurations analysed, maximum AEP losses in the range of 0.9–1.75% have been obtained. The AEP loss for the total degradation of the blade, are in fair agreement with those reported by Eisenberg et al. [8] and Papi et al. [12]. The variability of results obtained from the use of different LEP configurations, the uncertainty of the behaviour of each sample in the rain erosion whirling arm test, and the unpredictability of the response of the LEP under local rotor velocities lower than those tested guide the requirements for the optimisation of O&M towards a model that can be dynamically updated with inspection data.

The interest of this framework relies on its capability to be applied in the development stage for O&M cost estimation, and in the operation phase for O&M planning. The variability of the erosion degradation behaviour of the sample from the whirling arm test to its actual conditions can be overcome by updating the parameters of the power law with inspection or SHM data through Bayesian updates. Qualitative damage levels, which can be identified during blade inspections, can be mapped to erosion damage intervals and used to provide an estimate of the deterioration state of the blade at different sections that would serve to better capture the particular behaviour of the erosion process of the inspected blade and plan its maintenance accordingly; degradation caused by manufacturing defects can be also be corrected in the same way. This prognosis model can provide an estimation of the current power loss of the turbine due to this phenomenon and its expected

evolution, providing a tool to actively plan maintenance to avoid catastrophic failures of the blades and optimise the production of the wind turbine.

The upcoming steps of this research will be in O&M optimisation; wind turbine blade O&M will be dynamically optimised based on the proposed evolution of the erosion corrected with inspection data. At this point, the use of different strategies including reduced tip speed operation modes, different inspection intervals, and maintenance activities considering weather constraints and the uncertainty in weather and the performance of the erosion protection coatings will be analysed.

2.6.4 Reliability-based leading edge erosion maintenance strategy selection framework.

AUTHORS: Lopez, J. C., Kolios, A., Wang, L., Chiachio, M., Dimitrov, N.

JOURNAL: Applied Energy, 358, 122612. (2024).

LINK: https://www.sciencedirect.com/science/article/pii/S0306261923019761

SUMMARY OF MAIN OUTCOMES: A framework to evaluate and select calendar-based maintenance strategies for leading-edge erosion failures. This framework provides a practical tool for O&M practitioners to design a baseline strategy for this failure mode.

SUMMARY AND CONCLUSION: This paper presents a framework for site-specific analysis and O&M policy selection of LEE damage for wind turbine blades. This approach can serve to study different maintenance strategies at the planning stage, anticipate the degradation rates of different coating solutions and plan inspections/maintenance at the wind farm level. This framework is able to accommodate the uncertainty that lies in the coating behaviour and degradation dynamics, weather and maintenance success. The definition of a reliability function g(x) allows for the quantification of the PoF of the chosen maintenance strategies. By selecting the appropriate cost metric and combining it with the probability of failure, a maintenance strategy can be chosen by adjusting the balance between cost and PoF to meet the policy of the organisation in charge of the operation of the asset. While suboptimal policies are achieved by not considering the actual condition and material properties of the component of the turbine being operated, this can serve as a baseline for the O&M of the asset while policies based on inspection/SHM are deployed. The adoption of predictive maintenance techniques can be a complicated and costly task if not performed in a structured approach and counter-producing if not executed properly. Therefore, improvements in the O&M shall be deployed in a staged way and with the aid of pre-analysis based on models of the assets and the environment. The detailed knowledge of the dynamics of the most risk-critical failure modes requires an exhaustive analysis of all the uncertainties surrounding it. Once this knowledge is acquired, different failure modes can be analysed and combined through the use of surrogate models to provide computationally affordable representations of the asset that allow the study of combined failure modes.

Given the potentially catastrophic failures that a high-risk O&M policy can produce, numerical models emerge as a key tool to unveil further O&M cost reductions. Condition-based maintenance is more common for other components of the turbine such as the drivetrain, for which advanced data-based predictive models are developed, not without the difficulty of dealing with different parameters, logging frequencies and equipment manufacturers. In the case of the blade, it is not yet clear to the industry what failure modes to monitor, for which a risk analysis at the component level is highly important.

Given the highly dimensional state space that this problem entails, condition-based maintenance design is not a trivial task. A promising strategy to extract insightful information is the use of Reinforcement Learning (RL) agents to try to discover and exploit interesting policies. While this technique requires a careful definition of the problem, reward function and parameters among others, the outcomes can be of great importance for the iteration towards optimal policies. A promising follow-up study would be the comparison of the proposed maintenance strategies with condition-based policies discovered through autonomous decision-making systems.

2.7 ESR 8 Wen Wu

RESEARCH TOPIC: Modelling risk of failure using guided wave propagation and interaction with damage in complex composite structures.

HOST INSTITUTION: University of Nottingham, U.K.

ARTICLES SUBMITTED TO JOURNALS:

2.7.1 Guided waves-based damage identification in plates through an inverse Bayesian process.

AUTHORS: Wu, W., Malik, M. K., Cantero-Chinchilla, S., Lawrie, T., Yan, W. J., Tanner, G., ... & Chronopoulos, D.

JOURNAL: Ultrasonics, 125, 106773. (2022).

LINK: https://www.sciencedirect.com/science/article/pii/S0041624X22000816?via%3Dihub

SUMMARY OF MAIN OUTCOMES: A Bayesian inference framework for damage identification of plate structures with spherical symmetry is presented where a guided waves interaction model is used based on a semi-analytical approach.

SUMMARY AND CONCLUSION: In summary, a Bayesian inference framework for damage identification of plate structures with spherical symmetry is presented where a guided waves interaction model is used based on a semi-analytical approach. It combines Poisson theory and Kirchhoff theory producing the scattered field when a plane S0 wave forms the incident wave on a plate defect. The proposed framework is finally validated by a physical experiment and a full finite element model. The highly efficient framework shows excellent promise to build a fast digital twin that will be connected to the physical twin to support real-

time engineering decisions by capturing the impact of detected damage on structural performance and remaining useful life. The following conclusions are drawn from this paper:

- A fast Lamb-wave-based physics-informed damage identification framework in 2D structures for the first time is proposed, which can identify the geometry of a partly through-thickness circular hole in plate-like structures. The scattering coefficients of Lamb wave modes are reconstructed, and there is a strong correlation between the reconstructed and true values.
- Compared with a traditional finite element model and similar methods, the presented semi-analytical approach can greatly improve the robustness and efficiency of the inversion procedure for spherical symmetry damage without introducing more epistemic uncertainty.
- Physical ultrasound experiments for large Aluminium plates are conducted to extract wave reflection, and transmission coefficients with the aid of signal processing techniques. The use of features in the frequency domain has a clear physical meaning and is more computationally efficient than the time domain approaches.

2.7.2 Damage Quantification and Identification in Structural Joints through Ultrasonic Guided Wave-Based Features and an Inverse Bayesian Scheme

AUTHORS: Wen Wu, Sergio Cantero-Chinchilla, Wang-ji Yan, Manuel Chiachío Ruano, Rasa Remenyte-Prescott, Dimitiros Chronopoulos

JOURNAL: Sensors, 23(8), 4160. (2023).

LINK: https://www.mdpi.com/1424-8220/23/8/4160

SUMMARY OF MAIN OUTCOMES: A Bayesian inference framework is presented to identify the size of the circular hole in joints using frequency domain damage features.

SUMMARY AND CONCLUSION: In this paper, a Bayesian inference framework is presented for identifying the size of circular holes in joints using frequency-domain damage features. It is demonstrated that the guided wave monitoring technique is able to detect a circular hole in plate joints by exciting the steady-state waveform. A WFE model is presented to obtain the damage features numerically. To leverage the computational strategy, a kriging surrogate model is used within the Bayesian inversion scheme. Numerical and experimental studies are conducted to validate the proposed damage identification framework. In addition, the inferred accuracy as a function of sensor location is studied, finding that differences in sensor locations introduce uncertainties of varying magnitudes. In physical experiments, a pseudo-absorbing boundary condition was used to reduce the impact of boundary reflection waves on the scattering coefficient. The proposed physical model in this study theoretically avoids the influence of boundary reflection. However, when using this model, care should be taken to minimize the effect of boundary reflections on the results. Furthermore, the

WFE model employed in this study cannot handle joints with bolts or other discontinuous interfaces, as these may introduce complex scattering behaviour. The following conclusions can be drawn:

- The proposed framework provides a viable approach for damage characterization of bounded structures;
- The kriging surrogate model greatly improves the computational efficiency of the inversion process;
- The inversion error varies depending on the signal source.

Future research perspectives to be considered might include: combining a neural network model with the proposed WFE model to reduce the error of the simulated experimental results and investigating the effect of the frequency range on the inference error. However, selecting a suitable frequency range is beyond the scope of the current subject. We intend to investigate this topic further in our future work.

2.8 ESR 9 Juan Fernández

RESEARCH TOPIC: Paradigm-Shift Research for System-Level Real-Time Prognostics of Cyber-Physical Assets using Deep Learning approaches.

HOST INSTITUTION: University of Granada, Spain.

ARTICLES SUBMITTED TO JOURNALS:

2.8.1 Uncertainty quantification in Neural Networks by Approximate Bayesian Computation: Application to fatigue in composite materials.

AUTHORS: Juan Fernández, Manuel Chiachío, Juan Chiachío, Rafael Muñoz, Francisco Herrera

JOURNAL: Engineering Applications of Artificial Intelligence. (2022).

LINK: https://www.sciencedirect.com/science/article/pii/S0952197621003596?via%3Dihub

SUMMARY OF MAIN OUTCOMES: Development of a new training algorithm for artificial neural networks based on Bayesian methods. This is a gradient-free algorithm, that provides more flexibility and quantifies the uncertainty in the predictions in a realistic manner.

SUMMARY AND CONCLUSION: Modern ANN provide us with very accurate predictions, however, when these are used in a decision-making context, the quantification of the prediction uncertainty gains importance. It forms the basis to define the degree of belief in those predictions and helps us to decide how we make use of them. Many state-of-the-art Bayesian training algorithms use rigid parametric PDFs for the likelihood function and/or the weights and bias, such as a Gaussian PDF defined by their mean and standard deviation, which limits their capacity to represent the uncertainty in the observed data. Moreover, they are often subject to the drawbacks of gradient descent and backpropagation.

A novel training method for Bayesian Neural Networks has been developed in this paper using the Approximate Bayesian Computation combined with Subset Simulation as an inference engine. The resulting methodology, named here as BNN by ABC-SS, has been illustrated using two academic examples and applied to an engineering case study based on damage data in composite structures. The results have revealed that the non-parametric formulation of the likelihood function and the PDF of the weights provide a realistic uncertainty quantification according to the training data. Besides, through comparison with the VI method, HMC and PBP, BNN by ABC-SS showed more stability when making predictions, presumably due to the absence of gradient. Particularly for the composite fatigue damage case study, the proposed data-driven methodology can be seen as an alternative to purely physics-based models which fail at quantifying the real amount of uncertainty of this process.

This new training algorithm could become especially useful when applied to problems where a decision is significantly dependent on the amount of uncertainty. The scalability of the proposed method to train deep neural networks, with high-dimensional parameter spaces and large training data sets, could further extend the range of potential applications of this methodology and establish a natural continuation to this line of research.

2.8.2 Physics-guided Bayesian neural networks by ABC-SS: Application to reinforced concrete.

AUTHORS: Juan fernández, Juan Chiachío, Manuel Chiachío, Jose Barros, Matteo Corbetta

JOURNAL: Engineering Applications of Artificial Intelligence. (2023).

LINK: https://www.sciencedirect.com/science/article/pii/S0952197622007801

SUMMARY OF MAIN OUTCOMES: Development of a new hybrid algorithm that combines feed-forward artificial neural networks with physics-based models, and their application to structural assets. This algorithm is trained with Bayesian methods so that the uncertainty in the predictions is quantified.

SUMMARY AND CONCLUSION: This manuscript presented a new algorithm which combines BNN by ABC-SS with physics-based models, the so-called PG-BNN by ABC-SS. Unlike other physics-guided/informed neural networks where the physics is often introduced in the loss function or through boundary conditions, and then backpropagated during training, the proposed algorithm inserts the physics directly in the forward pass, which improves the extrapolation capabilities. Moreover, ABC-SS is a Bayesian gradient-free training method that provides the proposed algorithm with stability, flexibility and the ability to quantify the uncertainty. Those properties were evaluated in two experiments, where the accuracy of PG-BNN by ABC-SS was comparable to the benchmark SOTA PGNN trained with backpropagation, and outperformed significantly the performance of the purely physics-based and data-driven approaches.

The two main advantages of PG-BNN by ABC-SS, namely its ability to extrapolate outside the domain of the training data set and to quantify the uncertainty in the predictions, may improve significantly the subsequent decision-making process in engineering applications. The results of the engineering case study

showed the potential of the proposed algorithm to become if combined with visual inspections, an effective and fast tool to evaluate and diagnose the condition of structural elements after seismic events. Certainly, a tool that can anticipate the outcome of an event of which there is little data, with a defined degree of confidence, could be particularly useful in different engineering fields. Future research should focus on extending the proposed methodology to other types of artificial neural networks, as well as the application of ABC-SS training to high-dimensional parameter spaces. Also, the use of adaptive activation functions should be explored.

2.8.3 Physics-guided recurrent neural network trained with approximate Bayesian computation: A case study on structural response prognostics.

AUTHORS: Fernández, J., Chiachío, J., Barros, J., Chiachío, M., & Kulkarni, C. S.

JOURNAL: Reliability Engineering & System Safety, 243, 109822. (2024).

LINK: https://www.sciencedirect.com/science/article/pii/S0951832023007366

SUMMARY OF MAIN OUTCOMES: A new hybrid recurrent neural network combined with physics-based models for prognostics. This new methodology improves multi-step ahead forecasting, including the quantification of the uncertainty.

SUMMARY AND CONCLUSION: The success of RNN in all their different versions is unquestionable, however, their performance heavily relies on big training data sets, and those are a rare sight in the civil and structural engineering industry. Furthermore, the training process of the state-of-the-art RNN is based on the evaluation of a loss function and the use of the backpropagation algorithm, which implies some well-known drawbacks such as vanishing and exploding gradients, or reaching different local minima in each run of the algorithm, providing varying results.

In this manuscript, a novel physics-guided Bayesian RNN trained with ABC-SS was proposed. The physics-based models are introduced in the forward pass of the RNN, which mitigates the problems related to the lack of data and allows for extrapolation. This is especially important when multistep-ahead forecasting is required. At the same time, the use of ABC-SS as the learning engine translates into non-parametric probabilistic weights, Bayesian regularization, and probabilistic outputs with accurate quantification of the uncertainty. Also, the absence of gradient evaluation in ABC-SS allows for long-term dependencies to be learnt without the need for more complex architectures. The proposed Bayesian RNN has been applied to two different structural engineering experiments about fatigue damage progression in composites and seismic accelerations in reinforced concrete buildings. The results have shown that while PG-BRNN by ABC-SS provides comparable accuracy to the state-of-the-art PG-RNN, its predictions in different runs of the algorithm present very little deviation, resulting in a more reliable option. Also, when compared with its Bayesian competitor MC Dropout, the proposed algorithm provided a more precise and realistic quantification of the uncertainty. In relation to real-world applications, BRNN by ABC-SS could be explored as a quasi-real-time predictor for onboard SHM systems, provided that enough real data is available. Likewise, PG-BRNN by

ABC-SS has demonstrated the potential to become an on-site prediction tool for seismic events and/or aftershocks in buildings, thus helping to evaluate its structural integrity and the safety of the utility systems.

Finally, ABC-SS training is currently limited by the dimension of the parameter space, and may not be suitable to train very large RNNs with millions of neurons, such as those used for video activity recognition. Also, such complex model architectures would require a large number of samples N, which would result in a significant increase in computational cost. Considering those limitations, future lines of research should focus on solving the dimensional problem, potentially through new and more efficient sampling techniques. The computational cost could also be reduced if parallel computing was used during sampling. Lastly, the benefits of adding the forget, input and output gates to the forward pass of BRNN by ABC-SS, like in LSTM and GRU, may be assessed.

2.8.4 Training of physics-informed Bayesian neural networks with ABC-SS for prognostic of Li-ion batteries.

AUTHORS: Fernández, J., Corbetta, M., Kulkarni, C. S., Chiachío, J., & Chiachío, M.

JOURNAL: Computers in Industry, 155, 104058. (2024).

LINK: https://www.sciencedirect.com/science/article/pii/S0166361523002087

SUMMARY OF MAIN OUTCOMES: A new training method for physics-informed recurrent neural networks based on Bayesian methods. This new algorithm accounts for the uncertainty in both the data and the physics-based models, providing useful information for the decision-making process.

SUMMARY AND CONCLUSION: The demand for Li-ion batteries is increasing at a fast pace, mostly due to a surge in electric vehicles that use them for powering their engines, or operating their systems. For that very reason, new algorithms are constantly being developed to model the behaviour and performance of these batteries. Among those, PINNs are a promising line of research, as they benefit from both physics-based knowledge and data-driven approaches.

In this manuscript, a new Bayesian PINN is proposed, where the recurrent architecture presented in Nascimento et al. (2021) was modified and adapted to be trained with ABC-SS instead of backpropagation. This Bayesian training method provides non-parametric weights and avoids the formulation of a likelihood function, as well as the evaluation of its gradient. Those advantages translate into flexibility to adapt to the training data and a realistic and coherent quantification of the uncertainty. Nonetheless, the method still poses some challenges, such as the difficulties found to fit the last part of the non-ideal voltage curve during pre-training, or the computational inefficiencies during training and testing. Regarding pre-training, balancing the training data and/or using maximum absolute error as the metric function in ABC-SS proved to solve the issue satisfactorily. With respect to the computational inefficiencies, adjusting the recurrent cell architecture so the data-driven and physics-based parts could be run separately clearly accelerated the training process.

Furthermore, thanks to a multi-stage training approach, the physical parameters and the weights of the MLPs could be trained independently, which not only improved the computational cost of the hybrid model but also allowed for the uncertainty related to each type of parameter to be quantified in semi-isolation. This may also cast light on the relative importance of each parameter with respect to the others, with the potential to become a tool for evaluating the sensitivity of the model parameters. The experiment section demonstrated the accuracy of the proposed method, comparable to the standard backpropagation algorithm, as well as its ability to capture the uncertainty within the training data in a realistic manner.

Regarding future work, further research should undertaken about the aging effect in Li-ion batteries and how to include them in the proposed Bayesian hybrid model. Also, parallel computing should also be tested for the sampling stage, as it could also help to further reduce the overall computational cost of running the hybrid model.

2.9 ESR 10 Ali Saleh

RESEARCH TOPIC: Development of a prognostics-based self-adaptive Expert System for smart Composite Structures.

HOST INSTITUTION: University of Granada, Spain.

ARTICLES SUBMITTED TO JOURNALS:

2.9.1 Reduction of Petri net maintenance modelling complexity via approximate Bayesian computation.

AUTHORS: M. Chiachío, A. Saleh, S. Naybour, J. Chiachío, J. Andrews.

JOURNAL: Reliability Engineering & System Safety 222 108365. (2022)

LINK: https://www.sciencedirect.com/science/article/pii/S0951832022000436

SUMMARY OF MAIN OUTCOMES: Proposing a method to reduce the complexity of Petri nets by using the Approximate Bayesian Computation, which results in reduced computational cost.

SUMMARY AND CONCLUSION: A novel methodology was presented to allow the reduction of the complexity of PN models while retaining the behaviour of the models for key outputs. Given a proposed reduced PN model, the reduction was carried out through Approximate Bayesian Computation whereby a number of uncertain parameters from the reduced model were inferred based on the response of a reference PN. The inference was performed through an adaptive version of the ABC-SubSim algorithm which included a new method for sampling MCMC chain values to avoid manual calibration and preliminary trials besides preserving the statistical quality of the samples. An illustrative example has been provided to help the reader easily conceptualize the procedure, and a case study has been used to demonstrate some of the challenges faced in a real-world application. The following are some concluding remarks:

- The methodology can be applied to complex PN without restrictions (like HLPN) on the type of transitions that can be reduced;
- A set of candidate-reduced models proposed by the modeller can be assessed to give a comparative measure of their suitability;
- Further work can consider combining the proposed approach with alternative methods for quantifying the model similarity;
- More research is needed to explore optimal summary statistics to extend the application of the proposed method to extremely complex PN models.

2.9.2 Self-adaptative optimized maintenance of offshore wind turbines by intelligent Petri nets

AUTHORS: Ali Saleh, Manuel Chiachío Ruano, Juan Fernández Salas, Athanasios Kolios

JOURNAL: Reliability Engineering & System Safety, 231, 109013. (2023).

LINK: https://www.sciencedirect.com/science/article/pii/S0951832022006287?via%3Dihub

SUMMARY OF MAIN OUTCOMES: Optimized maintenance strategy for offshore wind turbines using Reinforcement learning and Petri nets.

SUMMARY AND CONCLUSION: A novel general methodology has been provided for combining RL with HLPN to form an intelligent PN model. The method, which has been named iPN, allows upgrading any conventional PN model, regardless of the number of states or actions, by gathering groups of transitions describing the conflicting actions in sets called action groups. The proposed methodology has been formulated in a general manner, however, this paper gave special focus to O&M problems, by providing specific treatment of practical O&M aspects within the iPN formulation. The method was used to autonomously find an optimum policy for the O&M of an OWT while considering different influencing factors. The following are some concluding remarks:

- The iPN algorithm has been able to deal with a final policy which makes an OWT availability equal to 99.4% while minimizing the maintenance costs, thus increasing the profits to the maximum;
- The iPN algorithm was able to learn when to trust the condition monitoring system based on the overall condition of the system. Also, it was able to recognize the probability of failure of each component based on their pattern of conditions and take maintenance actions accordingly;
- The created model was able to experience all the possible state–action pairs and evaluate each of them separately, creating a successful DSS that can address all possible scenarios;

- Further work can consider components' conditions based on continuous damage features, along with extending the proposed methodology to farms of OWTs based on heterogeneous components and subjected to varied degradation conditions;
- More research is needed to explore the use of data directly from CMS (i.e., raw data taken from installed sensors) within the iPN methodology, along with its reformulation to include PHM information, thus converting it as an intelligent predictive maintenance tool.

2.9.3 Intelligent and adaptive asset management model for railway sections using the ipn method.

AUTHORS: D. Prescott, R. Remenyte, M. Chiachio, A. Saleh.

JOURNAL: Reliability Engineering & System Safety 241 109687. (2024)

LINK: https://www.sciencedirect.com/science/article/abs/pii/S0951832023006014

SUMMARY OF MAIN OUTCOMES: Modeling the degradation of vertical geometry profile and ballast in railways while proposing an optimized maintenance strategy.

SUMMARY AND CONCLUSION: An *i*PN model was created for the maintenance and operation of railway sections while focusing on optimizing the maintenance of the ballast. This model is able to find the optimal maintenance strategy that can reduce the risk of being in undesired conditions while increasing revenues and decreasing costs. This paper also proposes several ideas to improve the computational efficiency of the model. A method to divide the PN into several subnets was proposed and found to be successful in reducing computational costs. Besides, each section of the railway was considered a separate environment that had its own RL elements. This allows the RL agents to focus only on the important aspects when making the decisions of each section and neglecting unnecessary information, which reduces the number of RL states. This, in turn, facilitates experience sharing between RL agents relating to sections of similar characteristics.

The model was applied to a practical problem and it shows the ability to reach an optimum maintenance strategy. The results show that it is crucial to avoid unnecessary maintenance actions because they can reduce the ballast age. This is because tamping and stoneblowing actions play a direct role in ballast fouling, which requires replacement once it becomes highly fouled. At the same time, the maintenance should be done before any risk of reaching a bad condition in order to avoid downtime or safety risks. A maintenance plan that gives the optimum decision as a function of various features of the railway section was found. This was able to avoid undesired conditions while increasing the age of each section and increasing the net profits per life of each section.

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3 Articles presented to international conferences

Presenting at prestigious conferences enhances a researcher's reputation within their academic community. It establishes them as an expert in their field and opens up opportunities for collaboration, funding, and career advancement. In the following section, a detailed list of the articles presented at congresses by the ESRs will provided.

3.1 ESR 1 Shankar Galiana

RESEARCH TOPIC: Reliable sensor networks for Structural Health Monitoring systems in highly loaded composite structures.

HOST INSTITUTION: German Aerospace Center (DLR)

ARTICLES SUBMITTED TO CONGRESSES:

3.1.1 Acousto-ultrasonic composite transducers integration into thermoplastic composite structures via ultrasonic welding

AUTHORS: Galiana, S., Moradi, M., Wierach, P., Zarouchas, D.

CONGRESS: 10th ECCOMAS Thematic Conference on Smart Structures and Materials 956-965, (2023), Patras, Greece.

LINK: https://elib.dlr.de/201886/

3.2 ESR 4 Tasdeeq Sofi

RESEARCH TOPIC: Novel procedure for designing, manufacturing and assembling smart composite wind turbine blades with embedded AU-SHM sensors.

HOST INSTITUTION: Foundation for Research, Development and Application of Composite Materials (FIDAMC)

ARTICLES SUBMITTED TO CONGRESSES:

3.2.1 Novel Procedure of Integrating Transducers to Thermoplastic Composite Structures by Induction Heating for SHM

AUTHORS: Sofi, T., Gude, M., Garcia, J., Wierach.

CONGRESS: In proceedings of the 10th ECCOMAS Thematic Conference on Smart Structures and Materials, Patras, Greece, 3-5 July 2023; pp. 1291-1302.

LINK: https://elib.dlr.de/201883/

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 859957.

3.3 ESR 5 Morteza Moradi

RESEARCH TOPIC: Prognostic signatures based on data-fusion techniques from Lamb-wave and acoustic emission in real-world FRP laminates subjected to random fatigue damage.

HOST INSTITUTION: Delft University of Technology (TU Delft)

ARTICLES SUBMITTED TO CONGRESSES:

3.3.1 Intelligent Health Indicators Based on Semi-supervised Learning Utilizing Acoustic Emission Data

AUTHORS: Moradi, M., Broer, A., Chiachío, J., Benedictus, R., & Zarouchas, D.

CONGRESS: In European Workshop on Structural Health Monitoring (pp. 419-428). Cham: Springer International Publishing. (2022, June), Palermo, Italy.

LINK: https://link.springer.com/chapter/10.1007/978-3-031-07322-9_43

3.3.2 Interpretable neural network with limited weights for constructing simple and explainable HI using SHM data

AUTHORS: Moradi, M., Komninos, P., Benedictus, R., & Zarouchas, D.

CONGRESS: In Annual Conference of the PHM Society (Vol. 14, No. 1). (2022, October), Nashville, USA

LINK: https://papers.phmsociety.org/index.php/phmconf/article/view/3185

3.3.3. Developing health indicators for composite structures based on a two-stage semi-supervised machine learning model using acoustic emission data.

AUTHORS: Moradi, M., Chiachío, J., & Zarouchas, D.

CONGRESS: In Proceedings of the 10th ECCOMAS Thematic Conference on Smart Structures and Materials (Vol. 10). (2023, July), Patras, Greece.

LINK:https://repository.tudelft.nl/islandora/object/uuid%3Ad3912853-0178-40ba-9735-d3699107c9cf

3.4 ESR 8 Wen Wu

RESEARCH TOPIC: Modelling risk of failure using guided wave propagation and interaction with damage in complex composite structures.

HOST INSTITUTION: University of Nottingham, U.K.

ARTICLES SUBMITTED TO CONGRESSES:

3.4.1 Asset management modelling approach integrating structural health monitoring data for composite components of wind turbine blades

AUTHORS: Wen Wu, Ali Saleh, Rasa Remenyte-Prescott

CONGRESS: 32nd European Safety and Reliability Conference. (2022), Dublin, Ireland

LINK: https://www.researchgate.net/publication/363267167

3.5 ESR 9 Juan Fernández

RESEARCH TOPIC: Paradigm-Shift Research for System-Level Real-Time Prognostics of Cyber-Physical Assets using Deep Learning approaches.

HOST INSTITUTION: University of Granada, Spain.

ARTICLES SUBMITTED TO CONGRESSES:

3.5.1 Probabilistic safety assessment in composite materials using BNN by ABC-SS.

AUTHORS: Juan Fernández, Juan Chiachío, Manuel Chiachío, Ali Saleh

CONGRESS: Annual Conference of the PHM Society, (2022), Nashville, USA

LINK: https://papers.phmsociety.org/index.php/phmconf/article/view/32754

3.6 ESR 10 Ali Saleh

RESEARCH TOPIC: Development of a prognostics-based self-adaptive Expert System for smart Composite Structures.

HOST INSTITUTION: University of Granada, Spain.

ARTICLES SUBMITTED TO CONGRESSES:

3.6.1 An assessment of different reinforcement learning methods for creating a decision support system based on the Petri net model.

AUTHORS: Ali Saleh, Manuel Chiachío.

CONGRESS: Annual Conference of the PHM Society, (2002), Nashville, USA

LINK: https://papers.phmsociety.org/index.php/phmconf/article/view/3240

3.6.2 Optimized Petri net model for condition-based maintenance of a turbine blade.

AUTHORS: A. Saleh, M. Chiachio, J. Chiachio.

CONGRESS: World Congress on Engineering Asset Management, Springer, pp. 657–664. (2022).

LINK: https://link.springer.com/chapter/10.1007/978-3-031-25448-2_61 Seville, Spain.

3.6.3 An optimized asset management petri net model for railway sections.

AUTHORS: D. Prescott, R. Remenyte, M. Chiachio, A. Saleh.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 859957.

CONGRESS: Materials Research Proceedings 27 (2023). The 9th Asia-Pacific Workshop on SHM, Cairns, Queensland, Australia.

LINK: https://www.mrforum.com/product/9781644902455-37/