## Editorial

## Special Issue: Uncertainty in PHM

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Uncertainty plays an important role in diagnostics, prognostics, and health management of engineering systems. The presence of uncertainty leads to an imprecise understanding of the behavior of such systems; as a result, this may adversely affect the results of diagnostics and prognostics. In particular, this may lead to an inaccurate estimation of the remaining useful life, which in turn affects operational decision-making. While several researchers have recognized the importance of uncertainty in prognostics and health management (PHM), there has not been a significant amount of research work that addresses the impact of uncertainty in different PHM activities. This is challenging because there are various sources of uncertainty that affect PHM, their interactions are not fully understood, and therefore, it is an arduous task to perform different PHM activities by systematically accounting for these sources of uncertainty. However, when this can be accomplished, it would be possible to estimate the uncertainty and confidence in the results of diagnostics and prognostics, and quantify the risk involved in prognostics-based decision-making.

This special issue on Uncertainty in PHM contains 11 excellent technical papers that investigate the impact of uncertainty on various PHM-related topics. These papers deal with new research for diagnostics and damage monitoring, prognostics, and post-prognostics activities such as decision-making. While some papers focus on developing fundamental research methods, some others focus on applications and investigate the role of uncertainty in PHM for those specific applications.

**Diagnostics and damage monitoring** deal with identifying the presence of anomalies during the operation of engineering systems. While such anomalies are commonly referred to as faults in certain disciplines such as electrical engineering, the term "damage" is more commonly used in some other disciplines such as structural and mechanical engineering. In many applications, damage identification is challenging because it is necessary to assess the presence and extent of damage based on signals available during the system operation. This process is further complicated by several sources of uncertainty that render signal processing extremely difficult. Hence, damage/fault diagnostics under uncertainty is one of the focal topics in this special issue, and there are four technical papers that exclusively address this challenging issue. First, a contribution by Tabrizi, Garibaldi, Fasana, and Marchesiello titled "A Novel feature extraction for anomaly detection of roller bearings based on performance improved Ensemble Empirical Mode Decomposition and Teager-Kaiser Energy Operator" develops pattern recognition methods based on Support Vector Machines, and illustrates the application of the proposed anomaly detection method to roller bearings. This paper combines several important statistical techniques and deals with the presence of uncertainty using classification techniques in order to focus on damage detection. Second, the manuscript from Gaudel, Chanthery, and Ribot titled "Hybrid particle Petri nets for systems health monitoring under uncertainty" develops a methodology based on Petri nets to facilitate model-based diagnosis in hybrid systems. Petri nets have been used for uncertainty quantification purposes and their application to prognostics and health management is innovative and promising, not only for diagnostics but also for prognostics. Third, the article by Schenkendorf and Groos titled "Global Sensitivity Analysis applied to Model Inversion Problems: A Contribution to

Rail Condition Monitoring", focuses on the application of variance decomposition and computation of Sobol's indices to Railroad damage monitoring problems. While sensitivity analysis methods have been applied to prognostics, this manuscript encourages the application of such methods to damage monitoring problems as well. Finally, Mishra, Vanli, and Park, in their article titled "A Multivariate Cumulative Sum Method for Continuous Damage Monitoring with Lamb-wave Sensors" employ feature extraction methods, principal component analysis, and various statistical measures to facilitate damage diagnostics.

The next important topic addressed is the development of new research methods for **prognostics and remaining useful life prediction**. In this special issue, two papers focus on the development of statistical uncertainty management methods that are applicable for prognostics and remaining useful life prediction. The article by Sankararaman and Goebel titled "Uncertainty in Prognostics and Systems Health Management" reviews the state-of-the-art in addressing uncertainty in prognostics and remaining useful life prediction. This article identifies the various sources of uncertainty that affect prognostics, and discusses what statistical methods can be used to quantify the combined effect of these sources of uncertainty on prognostics and remaining useful life prediction. Bartram and Mahadevan develop a Bayesian network-based approach for probabilistic prognosis in the article "Probabilistic Prognosis Using Dynamic Bayesian Networks". Dynamic Bayesian networks are based on the principles of conditional probability and total probability, and provide a mathematical framework for prognostics using both system-performance data and time-dependent state-space models that can be included within the Bayesian network.

Having calculated the remaining useful life, it is important to guide **post-prognostics activities** such as operational decision-making, fault mitigation, verification and validation, etc. In this special issue, there are two papers that focus on this topic. First, the article by Bole, Goebel, and Vachtsevanos authored an article titled "Controlling Tracking Performance for System Health Management - A Markov Decision Process Formulation" develops Markov Decision Processes for decision-making in the context of systems health management. Second, Vandawaker, Jacques, and Freels, in an article titled "Impact of Prognostic Uncertainty in System Health Monitoring" examine the impact of prediction accuracy uncertainty in remaining useful life prognostics for a squadron of aircraft. This is an important step in verification and validation processes, since the presence of uncertainty significantly complicates the verification/validation procedures and it is important to examine prediction accuracy to overcome this challenge.

In addition to the aforementioned papers that focus on the development of new research methods, this special issue also contains three papers that focus on specific applications in order to develop PHM methods. First, Acuña, Orchard, Silva, and Perez develop a new imputation method state of charge estimation during battery discharging in their article titled "Multiple-imputation-particle-filtering for Uncertainty Characterization in Battery State-of-Charge Estimation Problems with Missing Measurement Data: Performance Analysis and Impact on Prognostic Algorithms". The estimation of state-of-charge in batteries is a challenging task, especially when uncertainty is present, and this paper proposes a new statistical method based on imputation techniques to solve this problem. Second, Anilkumar, Singh, and Naikan, in their article titled "Effectiveness of vibration monitoring in the health assessment of induction motor" examine, using clustering techniques, whether vibration monitoring methods can alone properly diagnose the presence of faults in an induction motor. Finally, this special issue concludes with the contribution from Marhadi and Skrimpas, titled "Automatic Threshold Setting and Its Uncertainty Quantification in Wind Turbine Condition Monitoring System". Identifying optimal alarm thresholds in wind turbines is challenging, particular in the presence of uncertainty; this manuscript estimates both the alarm thresholds and the associated uncertainty to guide in the operation of wind turbines.

We, the editors, are confident that this special issue on Uncertainty in PHM significantly advances the state of research and development in this field through the dissemination of these research papers. The editors also express our sincere appreciation to the authors for their efforts in preparing and submitting these outstanding papers. We also thank the reviewers for their time and thoughtful feedback on all of these technical papers.

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**Biographies**

Dr. Shankar Sankararaman received his B.S. degree in Civil Engineering from the Indian Institute of Technology, Madras in India in 2007; and later, obtained his Ph.D. in Civil Engineering from Vanderbilt University, Nashville, Tennessee, U.S.A. in 2012. His research focuses on the various aspects of uncertainty quantification, integration, and management in different types of aerospace, mechanical, and civil engineering systems. His research interests include probabilistic methods, risk and reliability analysis, Bayesian networks, system health monitoring, diagnosis and prognosis, decision-making under uncertainty, treatment of epistemic uncertainty, and multidisciplinary analysis. His research contributions have been documented in over 80 conference articles, journal manuscripts, and book chapters. Currently, Shankar is a researcher at NASA Ames Research Center, Moffett Field, CA, where he develops algorithms for uncertainty assessment and management in the context of airspace safety analysis, and systems health management.

Dr. Sankaran Mahadevan is John R. Murray Sr. Professor of Engineering, Professor of Civil and Environmental Engineering, and Professor of Mechanical Engineering at Vanderbilt University. He also serves as Co-Director of the Laboratory for Systems Integrity and Reliability (LASIR) and is the founder-director of graduate studies in reliability and risk engineering and management, initially funded by the US National Science Foundation IGERT program. His research areas of interest are uncertainty quantification, risk and reliability methods, systems health monitoring, machine learning, and optimization under uncertainty. His research contributions during the past 30 years are documented in 500 technical publications, including two books and 230 journal articles. He is currently serving as Associate Editor for the *ASCE Journal of Engineering Mechanics*, *ASCE-ASME Journal of Risk and Uncertainty*, and *ASTM Journal on Smart and Sustainable Manufacturing*. He obtained his PhD from Georgia Institute of Technology, Atlanta in 1988.

Dr. Marcos E. Orchard is Associate Professor with the Department of Electrical Engineering at Universidad de Chile and was part of the Intelligent Control Systems Laboratory at The Georgia Institute of Technology. His current research interest is the design, implementation and testing of real-time frameworks for fault diagnosis and failure prognosis, with applications to battery management systems, mining industry, and finance. His fields of expertise include statistical process monitoring, parametric/non-parametric modeling, and system identification. His research work at the Georgia Institute of Technology was the foundation of novel real-time fault diagnosis and failure prognosis approaches based on particle filtering algorithms. He received his Ph.D. and M.S. degrees from The Georgia Institute of Technology, Atlanta, GA, in 2005 and 2007, respectively. He received his B.S. degree (1999) and a Civil Industrial Engineering degree with Electrical Major (2001) from Catholic University of Chile. Dr. Orchard has published more than 50 papers in his areas of expertise.