



FUNCTIONAL SAFETY STANDARDS COMMITTEE

PREDICTIVE MAINTENANCE IN THE CONTEXT OF FUNCTIONAL SAFETY

Authored by
FSSC Prognostics Working Group

TRADEMARKS AND DISCLAIMERS

IEEE believes the information in this publication is accurate as of its publication date; such information is subject to change without notice. IEEE is not responsible for any inadvertent errors.

The ideas and proposals in this specification are the respective author's views and do not represent the views of the affiliated organization.

ACKNOWLEDGMENTS

Special thanks are given to the following reviewers of this paper:

Jyotika Athavale
Mike Diaz
Luca Di Mauro
Carolina Di Napoli

Darren Galpin
Riccardo Mariani
Andrea Matteucci
Antonio Priore
Doria Ramadan

Federico Reghenzani
Baptiste Vignasse
Riccardo Vincelli
Jens Michael Warmuth

The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2024 by The Institute of Electrical and Electronics Engineers, Inc.

All rights reserved. 14 June 2024. Printed in the United States of America.

PDF: STDVA27052 979-8-8557-0885-1

IEEE is a registered trademark in the U. S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated. All other trademarks are the property of the respective trademark owners.

IEEE prohibits discrimination, harassment, and bullying. For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system, or otherwise, without the prior written permission of the publisher.

Find IEEE standards and standards-related product listings at: <http://standards.ieee.org>.

NOTICE AND DISCLAIMER OF LIABILITY CONCERNING THE USE OF IEEE SA DOCUMENTS

This IEEE Standards Association (“IEEE SA”) publication (“Work”) is not a consensus standard document. Specifically, this document is NOT AN IEEE STANDARD. Information contained in this Work has been created by, or obtained from, sources believed to be reliable, and reviewed by members of the activity that produced this Work. IEEE and the FSSC (Functional Safety Standards Committee) expressly disclaim all warranties (express, implied, and statutory) related to this Work, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; quality, accuracy, effectiveness, currency, or completeness of the Work or content within the Work. In addition, IEEE and the FSSC disclaim any and all conditions relating to: results; and workmanlike effort. This document is supplied “AS IS” and “WITH ALL FAULTS.”

Although the FSSC members who have created this Work believe that the information and guidance given in this Work serve as an enhancement to users, all persons must rely upon their own skill and judgment when making use of it. IN NO EVENT SHALL IEEE SA OR FSSC MEMBERS BE LIABLE FOR ANY ERRORS OR OMISSIONS OR DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF THIS WORK, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Further, information contained in this Work may be protected by intellectual property rights held by third parties or organizations, and the use of this information may require the user to negotiate with any such rights holders in order to legally acquire the rights to do so, and such rights holders may refuse to grant such rights. Attention is also called to the possibility that implementation of any or all this Work may require use of subject matter covered by patent rights. By publication of this Work, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. The IEEE is not responsible for identifying patent rights for which a license may be required, or for conducting inquiries into the legal validity or scope of patents claims. Users are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. No commitment to grant licenses under patent rights on a reasonable or non-discriminatory basis has been sought or received from any rights holder.

This Work is published with the understanding that IEEE and the FSSC members are supplying information through this Work, not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought. IEEE is not responsible for the statements and opinions advanced in this Work.

TABLE OF CONTENTS

1. PREDICTIVE MAINTENANCE	6
2. THE STATE OF THE ART OF FUNCTIONAL SAFETY REGARDING PDM	7
2.1. ISO/TR 9839:2023.....	7
3. REVIEW OF SELECTED REFERENCES	9
3.1. PROGNOSTICS: A LITERATURE REVIEW	9
3.2. A REVIEW: PROGNOSTICS AND HEALTH MANAGEMENT IN AUTOMOTIVE AND AEROSPACE	9
3.3. PROGNOSIS AND HEALTH MANAGEMENT OF ELECTRONICS	10
3.4. PROGNOSTICS AND HEALTH MANAGEMENT OF ENGINEERING SYSTEMS.....	10
3.5. MACHINE LEARNING FOR PREDICTIVE MAINTENANCE	11
3.6. IEEE STD 1856	11
4. OVERVIEW OF TECHNIQUES AND METRICS	13
5. CHALLENGES.....	16
6. PREDICTIVE MAINTENANCE APPLIED TO FUNCTIONAL SAFETY.....	17
6.1. PdM FOR SYSTEM AVAILABILITY.....	18
6.2. PdM AS SAFETY MECHANISM	19
6.3. ESTIMATION OF PdM EFFICIENCY	20
6.4. DEFINING TERMINOLOGY AND METRICS	21
7. CONCLUSIONS	25
8. REFERENCES	26
APPENDIX A – FAILURE MODE COVERAGE	27
APPENDIX B – PROGNOSTICS AND HEALTH MANAGEMENT SOCIETY	29

PREDICTIVE MAINTENANCE IN THE CONTEXT OF FUNCTIONAL SAFETY

ABSTRACT

The White Paper Study Group’s “Prognosis” supported by the IEEE FSSC prepared this paper to investigate the methodology of prognosis or preventive maintenance in the context of functional safety and mission-critical applications. The working group began work in April 2022 to identify potential uses and gaps in the state of the art of the current standards and to present recommendations to stakeholders.

This report does not review specific solutions or methodologies, nor define requirements for predictive maintenance applied in a functional safety context. The working group’s goal is to share its experiences while investing efforts to indirectly contribute to any standard organization or expert who define predictive maintenance best practices for functional safety, develop standard methodologies, and help establish common conventions across industry domains.

1. PREDICTIVE MAINTENANCE

Predictive Maintenance (PdM) is a strategy that uses data analysis and condition monitoring techniques to predict when maintenance activities should be performed on a system including electrical devices. PdM aims to identify potential errors or faults before they occur and take corrective action to prevent undesired effects such as system downtime, and reduce maintenance costs. This practice includes techniques such as condition monitoring, health monitoring, and prognostics to detect potential issues early and take appropriate corrective action. PdM is a potential tool for supporting the reliability and functional safety of electrical and electronic equipment because it may prevent faults from causing dangerous behavior in the system.

PdM involves monitoring the condition of an electronic system using various sensors and other monitoring tools and using data analysis techniques to identify trends and patterns that may indicate potential issues. This activity can include monitoring parameters such as temperature, frequencies, vibration, and electrical signals to detect anomalies that may indicate the early stages of a failure depending on the technology used for the construction of the system.

Once anomalies are identified and monitored, it is possible to predict when the potential issues can result in an error or a failure, and prevent it from happening by scheduling maintenance activities appropriately and conveniently. These activities can include repair or replacement, calibration, or reconditioning components. What actions to take can depend on current health and predictions: for example, a possible system reconfiguration might be turning off or redistributing the degraded functions, which aims to keep the system at minimum risk, but compromising on performance or functionality, until proper maintenance can be performed.

It is essential to understand that predictive techniques for Remaining Useful Life (RUL) can only be applied to failure modes associated with known degradation, wear-out, or known changes in the behavior and state of health. However, if the change in performance or health status can be measured over time, the eventual failure of the system or sub-system element can be predicted.

RUL predictive techniques target to predict the point in time at which a component or system is likely to fail and take action to prevent it. In the context of risk management and safety, PdM can help reduce the risk of equipment failure and improve system reliability and availability by identifying potential issues before they lead to safety incidents, hazards, or other problems. This can help developers achieve their safety goals and objectives while improving overall operational efficiency.

2. THE STATE OF THE ART OF FUNCTIONAL SAFETY REGARDING PDM

Functional safety standards, such as IEC 61508 [1] and ISO 26262 [2], primarily focus on preventing systematic faults by design and minimizing the risk of hazards resulting from faults that cannot be prevented during the operational life of a system.¹ They outline the requirements and methodologies for the development and validation of safety-critical systems, emphasizing the importance of hazard and risk analysis, safety requirements specification, design and implementation, verification and validation, and safety assessment.

The standards emphasize the importance of safety assurance, which must demonstrate that safety requirements were met through rigorous development and the assurance of the safety goals. Functional safety standards provide a critical foundation for ensuring the safety of safety-critical systems. By following the guidelines and requirements outlined in these standards, designers, and operators can develop and maintain systems that are safe and compliant with industry-known best practices.

However, both standards lack guidance on integrating predictive maintenance and prognostics techniques into the design, development, and maintenance of safety-critical systems. This gap is partly because prognostics and predictive maintenance are relatively new concepts in the functional safety field, and the technology and methods for implementing these concepts are still evolving. There are several challenges to implementing prognostics and predictive maintenance in safety-critical systems, such as data availability, model validation, and reliability estimation.

While the current state-of-the-art functional safety standards do not provide specific requirements for prognostics or predictive maintenance as a safety mechanism, future versions of these standards will likely incorporate specific recommendations and guidelines for these concepts.

2.1. ISO/TR 9839:2023

This document was prepared by the Technical Committee ISO TC22/SC32/WG8 and provides a survey of the current state of the art for *predictive maintenance techniques*. Approaches, normative references, industry

¹ The numbers in brackets correspond to the numbered references in Section 8.

standards, and technical publications are presented to consider degrading faults related to electrical/electronic hardware elements as a new type of fault and predictive maintenance techniques in an ISO 26262 safety argument. Much of the content is focused on semiconductors, but the concepts can be applied to other hardware elements.

This document includes the following:

- Terms and definitions about degrading faults.² It includes definitions of time intervals and RUL, sourcing the existing definitions such as those presented in IEEE Std 1856™-2017 [3]. It focuses on the important difference between measurable and un-measurable characteristics and, therefore on the classification of what can be considered as a degrading fault, i.e., a condition that evolves over time and can result in an error as its degradation exceeds a critical threshold.
- Survey of literature, industry standards, and technical publications about degrading faults and predictive maintenance. The collection of references provides a summary of the state-of-the-art understanding of monitoring non-constant and degradation over time of those characteristics, which can be used in health monitoring and predictive maintenance.
- Degrading fault lifecycle and how it can be linked with the bathtub curve reliability model.
- Quantifying the impact of degrading faults on base failure rate, under current requirements of the ISO 26262:2018, such as field-data usage and expert judgment.
- Impact of predictive maintenance applied as a predictive mechanism on random hardware metrics and diagnostic coverage.

The report also provides an informative approach to handling degrading faults, specifically a flow diagram for PdM as a safety mechanism to detect degrading faults and predict remaining useful life. The same diagram is used later in this white paper, with further considerations proposed by this working group, which combines the concepts and metrics described in the following sections.

² The authors of the paper ISO TR 9839 [13] define: “degrading fault, fault those characteristics are not constant and degrade over time, which can result in an error or failure when stimulated after degradation exceeds a critical threshold”. This white paper uses the same definition later in the section 6.2

3. REVIEW OF SELECTED REFERENCES

Recent advancements in sensor technology, remote communication, and computational capabilities, both on board and in the cloud, have significantly transformed the monitoring and management of system health in various domains, including automotive and avionics. This shift has led to an increasing emphasis on prognostics, wherein system degradation is forecasted through proactive techniques. This trend addresses the demands of original equipment manufacturers (OEMs) and end-customers who desire maximum availability and minimal total cost of ownership.

3.1. PROGNOSTICS: A LITERATURE REVIEW

The review article titled “Prognostics: A Literature Review” by Elatter, Elaminir, and Riad [4] is a valuable resource for researchers in the field of prognostics and Prognostics and Health Management (PHM). It provides a comprehensive overview of the current state of the field, covering various aspects such as methodologies, techniques, and applications.

Within the paper, the authors delve into a detailed examination of prognostics and PHM, including an analysis of different approaches and their effectiveness. The authors discuss the shift in maintenance strategies from reactive “fail & fix” methods to proactive “predict & prevent” approaches, highlighting the advantages of implementing prognostic techniques for system degradation forecasting.

Furthermore, the paper presents a comprehensive review of existing literature, summaries, and reports related to PHM. It offers a consolidated list of references, allowing researchers to explore further studies and gain a deeper understanding of the subject.

3.2. A REVIEW: PROGNOSTICS AND HEALTH MANAGEMENT IN AUTOMOTIVE AND AEROSPACE

The paper “A Review: Prognostics and Health Management in Automotive and Aerospace” by Kefalas, Apostolidis, Yang, and Othofer [5] provides an extensive compilation of references, summaries, and reports on PHM available online. The primary focus of this review is on the automotive industry, offering detailed insights into the progression from diagnostics to prognostics. Noteworthy examples include PHM applications for

electrical batteries, encompassing estimations of state-of-charge (SOC), capacity, and RUL, while emphasizing the significance of accurate measurement data. The paper also highlights the utilization of physical modeling approaches for suspension systems and data-driven techniques for other automotive components. Furthermore, it elaborates on the application of PHM in the aerospace sector, encompassing both physical and empirical approaches for complex systems like engines, airframes, and various aircraft components.

These papers serve as valuable resources for researchers new to the field of prognostics, providing a comprehensive overview of methodologies and practical examples.

3.3. PROGNOSIS AND HEALTH MANAGEMENT OF ELECTRONICS

“Prognostics and Health Management of Electronics” [6] provides an in-depth introduction to the field of prognostics and health management for electronics. The book covers topics such as the fundamentals of PHM, including the concepts of reliability, maintainability, and availability. It includes in-depth discussions of the mathematics and engineering principles underlying prognostics and health management. It also provides an overview of the various techniques used in PHM, including data-driven and model-based approaches. In addition to providing a comprehensive overview of the field of PHM, the book also includes case studies and examples that demonstrate the practical application of PHM in various industries, including aerospace, automotive, and telecommunications. It also covers the various strategies used for maintenance and repair, including corrective, preventive, and predictive maintenance.

3.4. PROGNOSTICS AND HEALTH MANAGEMENT OF ENGINEERING SYSTEMS

“Prognostics and Health Management of Engineering Systems” [7] introduces the field of prognostics and health management for engineering systems. The book covers fundamental concepts and techniques related to PHM, including sensor selection, signal processing, data fusion, feature extraction, model development, and decision-making. The authors present various case studies and applications to illustrate the practical implementation of PHM in real-world engineering systems, with examples and case studies. Kim, An, and Choi’s book takes a systematic and structured approach to the topic, emphasizing the integration of different techniques and methods.