

Preface

The remaining useful life (RUL) of a system is defined as the length from the current time to the end of the useful life. The concept of the RUL has been widely used in operational research, reliability, and statistics literature with important applications in other fields such as materials science, biostatistics, and econometrics. However, there are many definitions as what is regarded as the useful life. In ‘Businessdictionary.com,’ it defines the useful life “the period during which an asset or property is expected to be usable for the purpose it was acquired’. However, in accounting, it is defined as ‘the expected period of time during which a depreciating asset will be productive.” The keyword here is ‘usable’ or ‘productive’ which is again upon individual explanations. Clearly the definition of the useful life depends on the context and operational characteristics. In this book we will assume that the definition of the useful life is known to the owner of the asset and the main interest is to investigate the modeling methods for RUL estimation given condition and health monitoring information.

In conventional data-based approaches, estimating the RUL is achieved by evaluating the conditional lifetime distribution given that a system has survived up to a specific time. The obtained RUL distributions from these approaches are generally based on the life characteristics of a population of identical systems and lifetime data are required. However, such data are scarce in reality or even nonexistent at all for systems which are costly or time-consuming to collect the life data. With the advances in CM technologies, degradation data can be obtained from routine CM as feasible and low-cost alternatives to estimate the RUL. These data are usually correlated with the underlying physical degradation process. If they are properly modeled, degradation data can be used to predict unexpected failures and accurately estimate the lifetime of gradually degraded systems. In many situations, such as the drift degradation of an inertial navigation system used in the aerospace industry, it is natural to view the failure event of interest as the result of a stochastic degradation process crossing a threshold level, i.e., to model the hitting time of the degradation as a time-dependent stochastic process. On the other hand, dynamic environments induce changes in the physics of failure.

RUL prognosis is one of the key factors in condition-based maintenance (CBM), and prognostics and health management. It is critically important to assess the RUL of an asset while in use since it has impacts on the planning of maintenance activities, spare parts provision, operational performance, and profitability of the owner of an asset. RUL estimation has also an important role in the management of product reuse and recycle which has strategic impacts on energy consumption, raw material use, pollution, and landfill. The reused products must have sufficient long lives left among others to be able to be reused. This puts the importance of the estimation of RUL beyond CBM and prognostics and health management because of the green issues associated. As a consequence, developing RUL prognosis methods is much desired for health management of degrading systems to prevent sudden failure and reduce the safety risk. In the past four decades, valuable contributions to prognostics in reliability field have been made. This book is intended to summarize the research results studied mainly by the authors in the past decade.

This book introduces the main ideas of data-driven remaining useful life prognosis techniques, with an emphasis on stochastic models, methods, and applications. It gives a thorough survey of new methods that have been developed in the recent years and demonstrates them with examples. To the knowledge of the authors, all major aspects of RUL prognosis are treated for the first time in a single book from a common viewpoint. With the presentation of RUL prognosis methods for degrading systems, the book provides novel materials that have not yet been described in monographs or textbooks.

This monograph consists of four parts:

- **Part I: Introduction, Degradation Data Acquisition and Evaluation.** Advances in data-driven RUL prognosis techniques are reviewed. As fundamental issues for data-driven RUL prognosis, methods of how to acquiring the degradation data and how to evaluate the usability of the acquired data are presented.
- **Part II: Prognostic Techniques for Linear Degrading Systems.** Methods for adaptive RUL prognosis, exact RUL prognosis solution, RUL prognosis with multiple kinds of variability for linear degrading systems are presented and the methods are demonstrated by case studies.
- **Part III: Prognostic Techniques for Nonlinear Degrading Systems.** Methods for nonlinear degradation modeling, adaptive RUL prognosis, nonlinear RUL prognosis under multiple sources of variability, residual storage life prognosis with switching systems for nonlinear degrading systems are presented and the methods are demonstrated by case studies.
- **Part IV: Applications of Prognostic Information.** This part discusses the applications of prognostic information such as mission reliability estimation, condition-based replacement, spare parts forecasting, and joint optimization of spare part ordering and replacement.

As each of the models used requires its own mathematical background and the methods based on these models follow different lines of thinking, the book cannot present the methods for all details. The aim is to give the readers a broad view of the

field and provide them with bibliographical notes for further reading. A further reason for the different depth with which the chapters tackle the RUL prognosis problems is given by the status of research. In the introductory parts of all chapters, the problems to be solved are posed in a framework that is familiar to practicing engineers. They describe the new ideas and concepts of RUL prognosis in an intuitive way, before these ideas are brought into a strict mathematical form. Examples illustrate the applicability of the methods. Bibliographical notes at the end of each chapter point to the origins of the presented ideas and the current research lines. The evaluation of the methods and the application studies should help the readers to assess the available methods and the limits of the present knowledge about RUL prognosis with respect to their particular field of application.

Together with four parts, the book is composed of 16 chapters. Chapter 1 is devoted to an introduction to advances in data-driven RUL prognosis techniques. Chapter 2 considers the problem of planning repeated degradation test for degrading products with three-source variability. In Chap. 3, the attention is paid to specifying measurement errors for required lifetime estimation performance so as to evaluate the data usability. A linear degradation model with a recursive filter algorithm and Bayesian updating is presented to estimate the PDF of the RUL in Chap. 4. Chapter 5 derives the exact and closed-form solution of RUL prognosis for linear degrading systems. Chapter 6 presents a Wiener-process-based degradation modeling framework for RUL estimation with three-source variability. In Chap. 7, a diffusion process-based model was presented to characterize the dynamics and nonlinearity of degradation processes, and the corresponding RUL distribution is formulated. The results in Chap. 7 are further extended to an age- and state-dependent case in Chap. 8. In Chap. 9, an adaptive and nonlinear prognostic model is presented to estimate the RUL using the history of the observed data to date. Chapter 10 develops a real-time RUL estimation method based on a state space model considering that the degradation process is hidden and nonlinear. Chapter 11 presents a general nonlinear diffusion process-based model to estimate the RUL with the temporal variability, unit-to-unit variability, and measurement variability. In Chap. 12, the problem of predicting RSL for a class of systems with operation state switches is concerned. Chapter 13 applies the prognostic information to reliability estimation of phased-mission systems. In Chap. 14, a real-time variable cost-based maintenance model is presented based on nonlinear prognostic information. Chapter 15 presents an adaptive spare parts demand forecasting method based on degradation modeling of the CM data. In Chap. 16, a new sequential maintenance and inventory model is developed to consider the effects of both expectation of the maintenance cost and its variability under prognostic information.

In preparing the book, efforts have been made to maintain a balance between the required theoretical and mathematical rigor in the exposition of the methods and the clarity in the illustration of the numerical examples and practical applications. For this reason, this book can serve well as a reference to both reliability and risk analysis researchers and engineers. Furthermore, sufficient references leading to further studies are cited at the end of each chapter. This book will serve as a textbook and

reference book for graduate students and researchers in reliability and maintenance. Although the book is self-explanatory, a standard background in probability theory, mathematical statistics, and stochastic processes is recommended.

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