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Diagnosis and Fault-Tolerant Control by M. Blanke, M. Kinnaert, J. Lunze, and M. Staroswiecki, Springer-Verlag, 2003, ISBN: 3-540-01056-4. *Reviewed by Ramine Nikoukhah.*

Overview of Fault Detection

Security and reliability are of great importance in control system technology. To ensure a reasonable level of security and reliability, the need for failure detection (diagnosis) techniques has long been recognized. Roughly speaking, a failure is any kind of malfunction of the system that leads to unacceptable performance. Failure detection consists of techniques for determining whether a failure has occurred. These techniques provide the means for avoiding major breakdowns and enable the system operator to take appropriate action. Failure detection is used in high-performance systems such as aircraft control systems, power plants, and chemical plants. Not surprisingly, the development of reliable failure detection techniques has become an intensive field of research.

In model-based failure detection, the assumption is that a mathematical model of the behavior of the system under surveillance, in the absence of failure, is available. Failure detection then consists of deciding whether or not the measured inputs and outputs are consistent with this model. In most cases, a realistic model must account for uncertainty and noise, which implies that the input-output behavior is not just a single time trajectory but rather a set of time trajectories. This set is often difficult to characterize, making the detection decision difficult.

Failure detection has been widely studied, and the literature includes numerous books [3], [4], [7]–[9], [15], [20], [21] and survey articles [2], [10]–[14], [16], [19], [23]. In particular, the book [8] gives an up-to-date overview of the subject. The book reviewed here presents model-based methodologies for fault detection and fault-tolerant control; some of the methodologies can be found in the above literature while others are based on recent research papers.

Review of *Diagnosis and Fault-Tolerant Control*

The book by Blanke et. al covers several model-based failure detection techniques. Although failure detection is a well-defined challenge, the choice of system modeling technique can lead to quite different mathematical problems. A large portion of the book is devoted to presenting alternative modeling techniques.

Chapter 1 introduces the fundamental problems of failure detection and fault tolerant control and presents an overview of the ideas behind the methods presented in later chapters. Chapter 1 also provides comprehensive definitions of terminology for use throughout the book. What is missing in this chapter (and in the rest of the book), however, are examples of applications of the methods covered. It would have been useful to give real-world examples that utilize the methods presented; for example, method A is used in the brake system of car X, a variation of method B is used in the autopilot of airplane Y, or method C will be used in a future space station. On the other hand, Chapter 2 presents two examples used throughout the book and, although these applications cannot be considered industrial, they are sufficiently complex to illustrate some problems with implementation of the methods. The first example concerns fluid-level control in a two-tank system while the second example concerns steering control of a ship based on a simple model of the ship dynamics.

A review of some dynamical system models is given in Chapter 3. In particular, state-space continuous-time, discrete-time, discrete event, and hybrid systems are briefly discussed. Chapter 4 examines the application of some graphical analysis techniques to the study of fault propagation in component-based system architectures. The content of this chapter, however, seems unrelated to the rest of the book.

Chapter 5 considers continuous-time models and begins by deriving an interesting algorithm for finding redundancy among observed or known system variables that usually correspond to system inputs and outputs (u, y). The application of this algorithm to failure detection, however, is questionable because the redundancy relations involve first- and higher-order derivatives of u and y, information that cannot be obtained in many cases due to observation noise.

The main results concerning failure detection techniques are presented in Chapter 6. This chapter reviews techniques based on analytical redundancy, in particular, the classical two-stage detection method for dynamical systems subject to additive noise. The use of analytical redundancy in failure detection originated with [5] and [17]. The stochastic setting was considered in [18] where, with additive noise modeled as a stochastic white process, a two-stage detector was developed; the first stage consisted of a Kalman-based whitening filter generating a residual, and the second stage consisted of a canonical statistical test for deciding whether the residual had the expected statistical properties such as whiteness. A good picture of the early developments is given in the survey [23]. Unfortunately, the book does not make reference to these pioneering works. Many variants and extensions of the two-stage approach have been studied in the literature and some of these extensions are presented in this chapter. In some cases, algorithms for implementing the techniques are also given and several examples are used to illustrate their application.

Chapter 7 examines the fault-tolerant control problem. It is assumed that a finite number of faults is possible, and, for each fault, the dynamic behavior of the system is modeled as a continuous-time dynamical system. Switching between systems is modeled by an automaton, and the notions of passive and active fault tolerant control are introduced. Passive control is closely related to classical robust control in that behavioral changes due to failure are viewed as model uncertainty and are taken into account in the design of the controller. Active control, on the other hand, is based on controller reconfiguration subsequent to failure detection and identification. Two techniques are investigated, the first being an optimal control approach, which is considered only in the simple case of linear system, state feedback, and quadratic cost. The proposed method does not seem realistic for applications.

The second technique for fault-tolerant control is the virtual sensor-actuator. In the case of a sensor, the idea behind this technique is that, if a sensor fails, its output can be reconstructed from the other sensors, and the original controller can be used with the reconstructed observation. An analysis is presented for the limited case of static output feedback control. The applicability of this idea to the general dynamic feedback case is questionable; even stability properties do not seem to be preserved in the general case. The only general-purpose technique presented seems to be "the common sense approach," which involves designing a controller for each model and switching the controller after a change of model has been detected.

Chapter 8 explores a stochastic modeling technique for systems under surveillance. This technique uses a stochastic automaton with the Markov property, which is usually called a controlled Markov chain. Surprisingly, the authors never refer to the literature on Markov chains or, in particular, to the literature on the application of Markov chains to failure detection. Control of partially observed Markov chains is treated in [1]. For applications to failure detection; see, for example, [22] and [6]. Some elementary properties of Markov chains are derived in Chapter 8, and applications to the failure detection problem are discussed. The idea of a virtual sensor is also examined in this context.

In Chapter 9, the authors explore the supervision of a system where only quantized measurements of the inputs and outputs are available. This system is modeled as a stochastic automaton. Although this automaton does not have the Markov property, methods introduced in Chapter 8 are used for consideration of approximate models. There is no discussion, however, concerning stability. Finally, some of the methods discussed in earlier chapters are applied to examples introduced earlier.

Conclusions

With the exception of Chapter 6, which reviews classical results, most of the results presented are early ideas that have not been validated and developed into design techniques. This observation is particularly true for fault-tolerant control.

Nevertheless, the book is suited for those who want to begin researching failure detection and want to learn about some of the ideas examined recently in the literature. The reader should be aware that, contrary to what the title suggests, the book does not give a broad view of all the techniques used in diagnosis and fault-tolerant control, but rather focuses mainly on model-based methods. In addition, not all of the available model-based methods are considered; for example, those based on subspace methods and modal analysis are not covered. It should also be noted that the bibliography is not extensive; the majority of the 200+ references do not concern failure detection or fault-tolerant control directly but rather modeling, control, estimation, and identification.

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Matrix Riccati Equations in Control and Systems Theory by Hisham Abou-Kandil, Gerhard Freiling, Vlad Ionescu, and Gerhard Jank, Birkhäuser, Basel, Boston, Berlin, 2003, xx + 572, pp., ISBN: 3-7643-0085-X, US$149.00. *Reviewed by Leiba Rodman.*

The Riccati Differential Equation

In many undergraduate texts on differential equations, one often finds at least a passing mention (or sometimes a more in-depth treatment) of the Riccati differential equation. This nonlinear, first-order equation is of the form

$$\dot{x} = a(t)x^2 + b(t)x + c(t). \qquad (1)$$

This equation is named after Count Jacopo Francesco Riccati (1676–1754), an Italian nobleman, landowner, civic administrator, and father of 18 children, nine of whom survived into adulthood. Riccati himself studied several particular cases of (1), in particular with $a(t) = \alpha t^p$, $b(t) = 0$, $c(t) = \beta t^m$, where α and β are constants. Interesting information about Count Riccati's life and work, as well as a facsimile of one of his papers published in 1724, can be found in [1].

Although (1) generally cannot be solved in quadratures, it possesses remarkable properties. For example, the general solution, which depends on an arbitrary constant, is given by a linear fractional expression as a function of the constant. The equation was studied from a theoretical mathematical standpoint by many prominent mathematicians, among them Euler and Liouville. Earlier, it was studied by the Bernoullis.

In the second half of the 20th century, the role and place of the Riccati equation in mathematics, engineering, and science changed dramatically. It turns out that the *matrix* differential Riccati equation—that is, an equation of the general type (1) but with a matrix-valued, rather than scalar, unknown function $x(t)$—and the corresponding matrix *algebraic* Riccati equation play a key role in many applied problems. In the notation of the reviewed book, matrix differential and algebraic Riccati equations are written as

$$\dot{W} = M_{21}(t) + M_{22}(t)W - WM_{11}(t) - WM_{12}(t)W, \quad -\infty < t < \infty, \qquad (2)$$

and

$$0 = M_{21} + M_{22}W - WM_{11} - WM_{12}W. \qquad (3)$$

Here M_{ij} are given, suitably sized matrices, time varying or constant, as the case may be. The algebraic Riccati equation thus describes the equilibria of the corresponding differential Riccati equation. An early book by Reid [2] contains the fundamentals of this theory, with applications to random processes, optimal control, and diffusion problems.

Since the 1960s, the matrix differential and algebraic Riccati equations have enjoyed an ever-expanding range of applications. Besides important engineering science applications that today are considered classical, such as stochastic realization theory, optimal control, robust stabilization, and network synthesis, the newer applications include such areas as financial mathematics. The literature on the subject comprises thousands of items, including dozens of books. Recent monographs devoted largely to theoretical aspects of various types of Riccati equations include, besides the reviewed book, [3]–[8] (this list is admittedly far from complete). Additionally, there are several recent monographs on algorithmic and computational aspects of these equations.

The reviewed book focuses on the differential Riccati equation (2) and to a lesser extent the *difference* Riccati equation

$$W(k+1) = -M_{21} - M_{22}W(k) \times (I - M_{21}W(k))^{-1}M_{11}, \quad k = 0, \pm1, \pm2, \ldots,$$

as well as on the corresponding algebraic Riccati equation (3) and, again to a lesser extent,

$$W = -M_{21} - M_{22}W(I - M_{21}W)^{-1}M_{11}.$$

All Riccati equations considered in this book include matrix-valued coefficients. Basic properties of Riccati equations are addressed and several applications are studied in depth, including robust control, disturbance attenuation, game theory, and stochastic control. The text includes a description of the most recent research in this area. The subject matter is restricted to equations in finite-dimensional spaces [thus leaving out Riccati equations with possibly unbounded operator coefficients, which are of primary importance in optimal control of systems governed by partial differential equations (PDEs)] and to mainly theoretical issues (thus de-emphasizing numerical methods, although several numerical algorithms and examples are presented in detail). Within these restrictions, however, the book is a useful, timely, and welcome addition to the literature, as it collects many recent developments, especially on coupled and generalized equations, in book form. There is a lot of material that seems to be new, in particular, Chapters 7, 8, and 9.

The book will definitely become a standard reference for many aspects of the more advanced theory and applications of matrix Riccati equations. Overall, the exposition is written in a rigorous mathematical style. On the other hand, the book as a whole is clearly not intended for teaching, since there are few examples, no exercises, and the exposition is at times overbearing or cryptic. Nevertheless, an enthusiastic instructor could profitably use many nuggets of material in a graduate course for students in engineering and mathematics.

Now, let us turn to a more detailed description of the book's contents, chapter by chapter. The first two chapters contain rather standard material on the fundamentals of linear differential equations, Hamiltonian matrices, and algebraic Riccati equations. Nowadays, this material can be found in some form in many sources; see, for example, [5] for the algebraic Riccati equations. The third chapter explores global aspects of Riccati differential and difference equations. This chapter includes the study of flows on Grassmann manifolds and includes Riccati equations with periodic coefficients. A basic connection between Grassmanians and solutions W of (3) is encapsulated by the formula

$$\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} I \\ W \end{bmatrix} = \begin{bmatrix} I \\ W \end{bmatrix} (M_{11} + M_{12}W),$$

which recasts W in terms of the $\begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix}$-invariant subspace spanned by the columns of $\begin{bmatrix} I \\ W \end{bmatrix}$. A representation formula is given for the solutions of Riccati differential equations with constant coefficients.

A theory of Hermitian Riccati differential equations is expounded in Chapter 4. In particular, a complete proof is presented stating that the Riccati differential equation is essentially the only equation having the Loewner order preservation property. Chapter 5 takes up Riccati equations with periodic coefficients. Here, existence results for periodic equilibria are proved, and a description of positive-semidefinite periodic equilibria is given.

Coupled and generalized Riccati equations are investigated in Chapter 6. Several applications of the equations are described in this chapter as well, one of which concerns Markovian jump systems. The plant state equation for these systems has the form

$$\dot{x} = A(r(t))x(t) + B(r(t))u(t), \quad x(t_0) = x_0,$$

where x and u are the state and control vectors, respectively, and $r(t)$ is a Markov process taking values in a finite set that represents the plant mode. Other applications included in Chapter 6 are stochastic control and Nash and Stackelberg games. In contrast with Nash games, the players in Stackelberg games obey a hierarchical structure of leaders and followers.

The operator-based approach to symmetric differential Riccati equations is developed in Chapter 7. The Riccati theory, which, to quote the book, consists of "connections between stabilizing solutions to the symmetric algebraic Riccati equation, invertibility of the Toeplitz operator associated with the input-output operator of the underlying Hamiltonian system, and existence of antianalytic factorization of the Popov function," is presented in the context of time-varying and descriptor systems. The material in this chapter is in many ways an extension of the technical machinery and results developed in [7] for the time-invariant case.

The book addresses major applications for robust control in Chapter 8. The material here includes a thorough treatment of the four-block Nehari and disturbance-attenuation problems. Both problems have been closely studied in various contexts during the last three decades, and use many different mathematical techniques. As formulated in the book, the four-block Nehari problem consists of finding an upper norm bound for the input-output operator of the continuous-time, time-varying linear system

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"Model Reduction and Parameter Estimation for Diffusion Systems"
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$$\dot{x} = A(t)x + B_1(t)u_1 + B_2(t)u_2, \quad (4)$$

$$y_1 = C_1(t)x + D_{11}(t)u_1 + D_{12}(t)u_2, \quad (5)$$

$$y_2 = C_2(t)x + D_{21}(t)u_1 + D_{22}(t)u_2 \quad (6)$$

with inputs u_1, u_2 and outputs y_1, y_2, under exponentially stable additive perturbations of $A(t)$. Alternatively, for a given norm tolerance, the four-block Nehari problem seeks to determine whether or not there exists an input-output operator (as above) within the tolerance and, if it does exist, to describe all such input-output operators. The disturbance attenuation problem has to do with the norm bounds for the closed-loop input-output operator of (4), (5), (6) under suitably coupled stabilizing compensators. The approach of the text is based on the tools of Riccati theory.

Finally, Chapter 9 extends the Riccati theory to the nonsymmetric algebraic Riccati equation, with applications to game theory; in particular, open-loop Nash and Stackelberg equilibria are addressed.

The up-to-date bibliography is quite extensive, containing more than 400 entries. Unfortunately, consulting the bibliography is at times annoying because of a somewhat unusual quasi-alphabetical arrangement of items.

The reviewed book is highly recommended as a reference source for engineers and mathematicians on many aspects of the state of the art theory of matrix Riccati equations, and its many important applications.

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