

Comment on "The Sequential Estimation Technique"

In a recent correspondence [1], Pfeiffer raised the question, under what condition it makes sense to employ a sequential estimation technique similar to the Kalman-Bucy approach [2], [3]. He considers the sequence of random vectors $x(i)$, $i=0, 1, 2, \dots$, the discrete-time (unforced) vector process $\{x_i, i=1, 2, 3, \dots\}$, and assumes that the covariance matrices

$$P_{ij} = E[x_i x_j^T] \quad i \leq j \quad (1)$$

have been empirically obtained. The sensing device produces the data

$$y_i = A_i x_i, \quad A_i \text{ known}, \quad i = 1, 2, 3, \dots$$

It is then stated that the condition

$$P_{ii} P_{ii}^{-1} = P_{ii} P_{ii}^{-1} P_{ii} P_{ii}^{-1} \quad \text{for all } i \leq j \leq k \quad (2)$$

is necessary and sufficient for the linear, unbiased, minimum variance (LUMV) prediction of x_i , given the complete sequence $y^k, y^k = [y_1^T, \dots, y_k^T]^T$, to depend only on x_{i-1}^k . The x_i^k are the LUMV estimates of the x_i , given data up to and including time i . Using this fact, a sequential estimation theorem is proved in [1] for the LUMV estimate x_i^k of x_i given the complete sequence of data vectors y_1^k, \dots, y_i^k . The theorem consists of a set of equations in which the covariance matrices P_{ij} appear.

This correspondence is intended to show that Pfeiffer's theorem is not only similar to Kalman's result [2], but is equivalent to the case of pure filtering of the latter. It will be shown that under condition (2) a linear dynamic model for the $\{x_i\}$ process of the form assumed in [2] can easily be obtained, so that [2] is applicable.

To compare the model—also called shaping filter—from the given covariance matrices, let

$$P_{i+1,j} P_{i+1,j}^{-1} = R_{i+1,j} \quad \text{for all } j. \quad (3)$$

Now, condition (2) is postmultiplied by $P_{i+1,i}$ is set equal to $j=i+1$, and definition (3) is substituted:

$$P_{i+1,i} = R_{i+1,i} P_{i+1,i} = 0 \quad i \leq j. \quad (4)$$

Also, with i replaced by $i+1$:

$$P_{i+1,i+1} = R_{i+1,i+1} P_{i+1,i+1} = 0 \quad i < j. \quad (5)$$

Postmultiplying (4) by $R_{i+1,i}^{-1}$, subtracting the result from (5), and remembering (1), it follows

$$\begin{aligned} K_i^T [x_{i+1} - R_{i+1,i+1} x_i] x_i^T \\ = E[(x_{i+1} - R_{i+1,i+1} x_i) x_i^T] = 0 \end{aligned} \quad \text{for all } i < j. \quad (6)$$

With the definition

$$x_{i+1} = R_{i+1,i} x_i + w_i \quad \text{for all } j \quad (7)$$

it follows from (6) that $\{w_i\}$ is a vector-valued white noise process:

$$E[w_i w_j^T] = 0 \quad i < j. \quad (8)$$

To find its covariance matrix for $i=j$, (7)

is used together with (3):

$$Q_i = E[w_i w_i^T] = P_{i+1,i+1} - R_{i+1,i+1} P_{i+1,i}^{-1} R_{i+1,i}^T. \quad (9)$$

Equations (7) and (8) define a linear dynamic model excited by white noise. The matrices $R_{i+1,i}$ and Q_i can be recognized from the given covariance matrices P_{ij} by (3) and (9).

Since Kalman's results hold for the LUMV estimator, too, theorem 3 of [2] can be applied. For the special case of pure filtering, that theorem says, in the terminology of [1]: The optimal estimate x_i^k of x_i , given y_1^k, \dots, y_i^k , generated by

$$x_{i+1} = R_{i+1,i} x_i + D_i (y_i - A_i x_i) \quad (10)$$

$$\hat{x}_{i+1} = R_{i+1,i} \hat{x}_i + D_i (y_i - A_i \hat{x}_i) \quad (11)$$

$$D_i = (R_{i+1,i} \hat{A}_i A_i^T (A_i \hat{A}_i A_i^T)^{-1})^T \quad (12)$$

$$\hat{A}_i = (R_{i+1,i} - D_i A_i) \hat{A}_{i-1} R_{i+1,i}^{-1} + Q_i \quad (13)$$

where \hat{A}_i is the optimal estimate of x_i given the data y_1^i, \dots, y_i^i (one step ahead prediction) and \hat{A}_i is defined as the covariance matrix of the error $x_i - \hat{x}_i$.

To identify the result of [1] with this, (11) and (12) are substituted in (10):

$$x_{i+1} = \hat{x}_i + \hat{A}_i A_i^T (A_i \hat{A}_i A_i^T)^{-1} (y_i - A_i \hat{x}_i) \quad (14)$$

where, by (10)

$$\hat{x}_i = R_{i+1,i} x_{i-1}^k. \quad (15)$$

Next, the relation between \hat{A}_i and the covariance matrix A_i^k of the error $x_i - x_i^k$ is established with the aid of (7) and (15):

$$\begin{aligned} R_{i+1,i} &= A_i^k (A_i^k)^{-1} R_{i+1,i}^T \\ &= R_{i+1,i} E[(x_{i+1} - x_i^k)(x_{i+1} - x_i^k)^T] R_{i+1,i}^T \\ &= E[(x_{i+1} - x_{i+1}^k - x_i^k)(x_{i+1} - x_{i+1}^k - x_i^k)^T] \\ &= A_{i+1} - Q_{i+1} \end{aligned}$$

because $E[(x_{i+1} - x_{i+1}^k)(x_i^k)^T] = Q_{i+1}$. With (9) and (3) it follows

$$\begin{aligned} \hat{A}_i &= P_{i+1,i} - R_{i+1,i} (P_{i+1,i+1})^{-1} \\ &= A_{i+1} R_{i+1,i+1}^{-1} \end{aligned} \quad (16)$$

Finally, in above equation for $\hat{A}_i - Q_{i+1}$, x is replaced by $x+1$, (13) is used, (16) is substituted and the result is pre- and postmultiplied by the inverse of $R_{i+1,i}$ and $R_{i+1,i}^T$:

$$A_i^k = \hat{A}_i - \hat{A}_i A_i^T (A_i \hat{A}_i A_i^T)^{-1} A_i A_i^T. \quad (17)$$

Equations (14)–(17) form the sequential estimation theorem in [1].

It should be noted, however, that in (10) and in the derivation of (17) the existence of the inverse of $R_{i+1,i}$ is required. In [1] this inverse is not needed, so that Pfeiffer's result also covers the noninvertible case when $R_{i+1,i}$ is singular. For example, the problem in [2], page 43, where

$$R_{i+1,i} = \begin{bmatrix} \sigma^2 & 0 \\ 0 & 0 \end{bmatrix} \quad x_i = [1 \quad 1]^T x_{i-1}$$

which is computed there for the case of one step ahead prediction, can be solved by [1] for pure filtering, too.

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Author's Reply

Brändlich is correct in pointing out that any discrete stochastic process which has the sequential correlation property, see (2) in the foregoing, can be modeled as a discrete linear dynamic system excited by uncorrelated disturbances. Thus the sequential estimation theorem defines those processes which can be treated by Kalman's method [2], and Brändlich has shown how to construct the dynamic model of such a process from empirically obtained statistics. It should be pointed out, however, that the continuous form of the estimator which follows from the sequential estimation theorem is not directly equivalent to that obtained in [2]. In order to derive the continuous estimator, Kalman and Bucy assumed that the data is contaminated by additive white noise, where the normalized correlation matrix contains Dirac delta functions. Such measurement noise is not meaningful in the context of [1] for, mathematically, the product of Dirac delta functions is not defined, and, intuitively, such data could not be obtained from a physically realizable system. Instead, the appropriate continuous linear model is

$$dx = f(x)dt + dw \quad (18)$$

$$dy = A(x) + dw/dt \quad (19)$$

where $dw = dW(t)/dt$ is the data; $x(t)$ is the state vector; $A(t)$ is a given matrix; dw/dt refers to the change of W in time dt ; $A(t) = [A(t), dy/dt]$ evaluated at $t = 0$; $R(t, s)$ is the continuous form of the normalized correlation matrix, (3) in the foregoing, and the dw/dt are uncorrelated increments, with $E[dW(t)] = 0$ and $E[dW(t)dW(s)^T] = Q(t)dt$. The $Q(t)$ is the continuous form of (9). Thus the estimator obtained in [4] is only equivalent to the Kalman and Bucy form if the data vector of (3) is interpreted to be dy/dt . Correlation between process and measurement noise is introduced, and appropriate manipulations are performed [5]. For practical applications, the observation data derivative term can be eliminated by putting the estimator into its integral form and integrating (more precisely, summing) by parts [4].

These considerations are important when one is confronted with the not unrelated task of constructing an intuitively reasonable stochastic model of a control system from rather sparse empirical data, and then designing an estimator suitable for the model.

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Sequential Estimation

John L. Crassidis, John L. Junkins



Sequential Estimation:

Sequential Estimation Malay Ghosh, Nitis Mukhopadhyay, Pranab Kumar Sen, 2011-09-09 The only comprehensive guide to the theory and practice of one of today's most important probabilistic techniques The past 15 years have witnessed many significant advances in sequential estimation especially in the areas of three stage and nonparametric methodology Yet until now there were no references devoted exclusively to this rapidly growing statistical field Sequential Estimation is the first single source guide to the theory and practice of both classical and modern sequential estimation techniques including parametric and nonparametric methods Researchers in sequential analysis will appreciate the unified logically integrated treatment of the subject as well as coverage of important contemporary procedures not covered in more general sequential analysis texts such as Shrinkage estimation Empirical and hierarchical Bayes procedures Multistage sampling and accelerated sampling procedures Time sequential estimation Sequential estimation in finite population sampling Reliability estimation and capture recapture methodologies leading to sequential tagging schemes An indispensable resource for researchers in sequential analysis Sequential Estimation is an ideal graduate level text as well *Sequential statistics* Z. Govindarajulu, 2004 This book contains topics that can be covered in a single semester course Only elementary proofs are provided and thus the mathematics and statistics are maintained at a basic level Only a course in each of three areas advanced calculus probability and statistical inference is assumed of the student The book has a chapter on applications to biostatistics and a supplement presenting computer programs for selected sequential procedures Identified problems are provided at the end of each chapter

Factorization Methods for Discrete Sequential Estimation Gerald J Bierman, 1977-05-04 Kalman's elegant solution of the discrete linear estimation problem has had a major impact in academic engineering circles and in the aerospace industry Recently areas of application have widened to include such diverse subjects as transportation planning and scheduling marine and satellite navigation power systems process control surveying earthquake prediction communications economic forecasting and analysis water resource planning human modeling and biomedical applications Unfortunately numeric accuracy and stability problems have often prevented researchers in these diverse disciplines from successfully computer mechanizing Kalman's algorithms It has come to be realized that algorithm formulations that involve matrix factorization generally enhance numeric characteristics and at the same time generate new analytical perceptions Our aim in this monograph is to familiarize analysts in these various areas with those matrix factorization techniques that lead to estimation algorithms that are efficient economical reliable and flexible In order to expedite their application we have included FORTRAN descriptions of the important algorithms Our experience leads us to conclude that a better understanding of the underlying mathematics involved with matrix factorization together with an awareness of the concise FORTRAN implementations that are possible will result in a more widespread utilization of this technology Hopefully after familiarizing himself with this material the reader will share our opinion This monograph came

about as a result of a set of lectures on leastsquares estimation that I gave at the Jet Propulsion Laboratory The interest with which these lectures were received convinced me that the estimation applications community would benefit from and in fact was in need of an estimation reference book that thoroughly describes those matrix factorization methods and associated numerical techniques that have been successfully employed by numerical analysts Emphasis in this book has been on the algorithmic and computational aspects of discrete linear estimation Although our material is of a rather specialized nature it is of interest to a diverse audience Our pragmatically oriented and detailed presentation will we hope make this book a useful reference

Theory and Applications of Sequential Nonparametrics Pranab Kumar Sen,1985-01-31 A study of sequential nonparametric methods emphasizing the unified Martingale approach to the theory with a detailed explanation of major applications including problems arising in clinical trials life testing experimentation survival analysis classical sequential analysis and other areas of applied statistics and biostatistics

Sequential Estimation of the Mean of a Normal Population Herbert Robbins,1958

Stated Choice Methods Jordan J. Louviere,David A. Hensher,Joffre D. Swait,2000-09-28 Understanding and predicting the behaviour of decision makers when choosing among discrete goods has been one of the most fruitful areas of applied research over the last thirty years An understanding of individual consumer behaviour can lead to significant changes in product or service design pricing strategy distribution channel and communication strategy selection as well as public welfare analysis This graduate and practitioner guide first published in 2000 deals with the study and prediction of consumer choice behaviour concentrating on stated preference SP methods placing decision makers in controlled experiments that yield hypothetical choices rather than revealed preferences RP actual choices in the market It shows how SP methods can be implemented from experimental design to econometric modelling and suggests how to combine RP and SP data to get the best from each type The book also presents an update of econometric approaches to choice modelling

Encyclopedia of Epidemiologic Methods Mitchell H. Gail,Jacques Benichou,2000-11-02 Featuring articles from the prestigious Encyclopedia of Biostatistics many of which have been revised and updated to include recent developments the Encyclopedia of Epidemiologic Methods also includes newly commissioned articles reflecting the latest thinking in Cancer Registries Birth Defect Registries Meta Analysis of Epidemiologic Studies Epidemiology Overview Sample Size Sex Ratio at Birth Software Design and Analysis Featuring contributions from leading experts in academia government and industry the Encyclopedia of Epidemiologic Methods has been designed to complement existing texts on the subject by providing further extensive up to date coverage of specialised topics and by introducing the reader to the research literature Offering a wealth of information in a single resource the Encyclopedia of Epidemiologic Methods Offers an excellent introduction to a vast array of specialised topics Includes in depth coverage of the statistical underpinnings of contemporary epidemiologic methods Provides concise definitions and introductions to numerous concepts found in the current literature Uses extensive cross references helping to facilitate further research and enabling the reader to locate

definitions and related concepts In addition to featuring extensive articles in the areas of descriptive and analytic epidemiology the Encyclopedia also provides the reader with articles on case control design and offers substantial coverage of allied statistical methods

Sequential Statistical Procedures Z. Govindarajulu, 2014-06-20 Probability and Mathematical Statistics Volume 26 Sequential Statistical Procedures provides information pertinent to the sequential procedures that are concerned with statistical analysis of data This book discusses the fundamental aspects of sequential estimation Organized into four chapters this volume begins with an overview of the essential feature of sequential procedure This text then examines the sequential probability ratio test procedure and provides a method of constructing a most powerful test for a simple hypothesis versus simple alternative testing problem Other chapters consider the problem of testing a composite hypothesis against a composite alternative This book discusses as well the theory of sequential tests that is appropriate for distinguishing between two simple or composite hypotheses The final chapter deals with the theory of sequential estimation This book is a valuable resource for graduate students research workers and users of sequential procedures

Exponential Distribution K. Balakrishnan, 2019-01-22 The exponential distribution is one of the most significant and widely used distribution in statistical practice It possesses several important statistical properties and yet exhibits great mathematical tractability This volume provides a systematic and comprehensive synthesis of the diverse literature on the theory and applications of the expon

Change-Point Analysis in Nonstationary Stochastic Models Boris Brodsky, 2016-12-12 This book covers the development of methods for detection and estimation of changes in complex systems These systems are generally described by nonstationary stochastic models which comprise both static and dynamic regimes linear and nonlinear dynamics and constant and time variant structures of such systems It covers both retrospective and sequential problems particularly theoretical methods of optimal detection Such methods are constructed and their characteristics are analyzed both theoretically and experimentally Suitable for researchers working in change point analysis and stochastic modelling the book includes theoretical details combined with computer simulations and practical applications Its rigorous approach will be appreciated by those looking to delve into the details of the methods as well as those looking to apply them

Guide to Wireless Sensor Networks Sudip Misra, Isaac Woungang, Subhas Chandra Misra, 2009-05-29 Overview and Goals Wireless communication technologies are undergoing rapid advancements The last few years have experienced a steep growth in research in the area of wireless sensor networks WSNs In WSNs communication takes place with the help of spatially distributed autonomous sensor nodes equipped to sense specific information WSNs especially the ones that have gained much popularity in the recent years are typically ad hoc in nature and they inherit many characteristics features of wireless ad hoc networks such as the ability for infrastructure less setup minimal or no reliance on network planning and the ability of the nodes to self organize and self configure without the involvement of a centralized network manager router access point or a switch These features help to set up WSNs fast in situations where there is no existing network setup or in times when

setting up a fixed infrastructure network is considered infeasible for example in times of emergency or during relief operations WSNs find a variety of applications in both the military and the civilian population worldwide such as in cases of enemy intrusion in the battlefield object tracking habitat monitoring patient monitoring fire detection and so on Even though sensor networks have emerged to be attractive and they hold great promises for our future there are several challenges that need to be addressed Some of the well known challenges are attributed to issues relating to coverage and deployment scalability quality of service size computational power energy efficiency and security

Optimal Estimation of Dynamic Systems

John L. Crassidis, John L. Junkins, 2004-04-27 Most newcomers to the field of linear stochastic estimation go through a difficult process in understanding and applying the theory This book minimizes the process while introducing the fundamentals of optimal estimation Optimal Estimation of Dynamic Systems explores topics that are important in the field of control where the signals received are used to determine highly sensitive processes such as the flight path of a plane the orbit of a space vehicle or the control of a machine The authors use dynamic models from mechanical and aerospace engineering to provide immediate results of estimation concepts with a minimal reliance on mathematical skills The book documents the development of the central concepts and methods of optimal estimation theory in a manner accessible to engineering students applied mathematicians and practicing engineers It includes rigorous theoretical derivations and a significant amount of qualitative discussion and judgements It also presents prototype algorithms giving detail and discussion to stimulate development of efficient computer programs and intelligent use of them This book illustrates the application of optimal estimation methods to problems with varying degrees of analytical and numerical difficulty It compares various approaches to help develop a feel for the absolute and relative utility of different methods and provides many applications in the fields of aerospace mechanical and electrical engineering

Encyclopedia of Statistical Sciences, Volume

12, 2005-12-16 ENCYCLOPEDIA OF STATISTICAL SCIENCES

Statistics and Control of Random Processes

A. A. Novikov, Al'bert Nikolaevich Shirinkin, 1994 This book contains papers by participants in two seminars one on martingales and statistics of stochastic processes and one on sequential analysis both of which were held at the Steklov Institute of the Russian Academy of Sciences The papers develop the concepts of martingales and semimartingales and stochastic calculus for them as well as their applications in statistics and control of stochastic processes The class of semimartingales that is the class of all processes which can be represented as a sum of a martingale and a process with bounded variation is rather large It contains such important processes as Brownian motion Poisson processes solutions of stochastic differential equations and others The papers treat theoretical aspects of statistics of stochastic processes as well as specific models of stochastic processes from the standpoint of their statistics and control The collection is intended for undergraduate and graduate students and researchers in probability theory and mathematical statistics

Discrete Choice Methods with Simulation

Kenneth Train, 2003-01-13 Table of contents

Optimal Estimation of Dynamic Systems, Second Edition

John L.

Crassidis, John L. Junkins, 2011-10-26 Optimal Estimation of Dynamic Systems Second Edition highlights the importance of both physical and numerical modeling in solving dynamics based estimation problems found in engineering systems Accessible to engineering students applied mathematicians and practicing engineers the text presents the central concepts and methods of optimal estimation theory and applies the methods to problems with varying degrees of analytical and numerical difficulty Different approaches are often compared to show their absolute and relative utility The authors also offer prototype algorithms to stimulate the development and proper use of efficient computer programs MATLAB codes for the examples are available on the book s website New to the Second Edition With more than 100 pages of new material this reorganized edition expands upon the best selling original to include comprehensive developments and updates It incorporates new theoretical results an entirely new chapter on advanced sequential state estimation and additional examples and exercises An ideal self study guide for practicing engineers as well as senior undergraduate and beginning graduate students the book introduces the fundamentals of estimation and helps newcomers to understand the relationships between the estimation and modeling of dynamical systems It also illustrates the application of the theory to real world situations such as spacecraft attitude determination GPS navigation orbit determination and aircraft tracking **Joint Statistical Papers of Akahira and Takeuchi** Masafumi Akahira, Kei Takeuchi, 2003 Masafumi Akahira and Kei Takeuchi have collaborated in research on mathematical statistics for nearly thirty years and have published many articles and papers This volume is a collection of their papers some published in well known and others in lesser known journals The papers cover various fields but the main subject is the theory of estimation asymptotic non regular sequential etc All the papers are theoretical in nature but have implications for applied problems Essays in Honor of Joon Y. Park Yoosoon Chang, Sokbae Lee, J. Isaac Miller, 2023-04-24 Volumes 45a and 45b of Advances in Econometrics honor Professor Joon Y Park who has made numerous and substantive contributions to the field of econometrics over a career spanning four decades since the 1980s and counting *Selected Papers* Herbert Robbins, 2012-12-06 Herbert Robbins is widely recognized as one of the most creative and original mathematical statisticians of our time The purpose of this book is to reprint on the occasion of his seventieth birthday some of his most outstanding research In making selections for reprinting we have tried to keep in mind three potential audiences 1 the historian who would like to know Robbins seminal role in stimulating a substantial proportion of current research in mathematical statistics 2 the novice who would like a readable conceptually oriented introduction to these subjects and 3 the expert who would like to have useful reference material in a single collection In many cases the needs of the first two groups can be met simultaneously A distinguishing feature of Robbins research is its daring originality which literally creates new specialties for subsequent generations of statisticians to explore Often these seminal papers are also models of exposition serving to introduce the reader in the simplest possible context to ideas that are important for contemporary research in the field An example is the paper of Robbins and Monroe which initiated the subject of stochastic

approximation We have also attempted to provide some useful guidance to the literature in various subjects by supplying additional references particularly to books and survey articles with some remarks about important developments in these areas ,

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