

A Bayesian Theory of Change Detection in Statistically Periodic Random Processes

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Abstract—A new class of stochastic processes called independent and periodically identically distributed (i.p.i.d.) processes is defined to capture periodically varying statistical behavior. A novel Bayesian theory is developed for detecting a change in the distribution of an i.p.i.d. process. It is shown that the Bayesian change point problem can be expressed as a problem of optimal control of a Markov decision process (MDP) with periodic transition and cost structures. Optimal control theory is developed for periodic MDPs for discounted and undiscounted total cost criteria. A fixed-point equation is obtained that is satisfied by the optimal cost function. It is shown that the optimal policy for the MDP is nonstationary but periodic in nature. A value iteration algorithm is obtained to compute the optimal cost function. The results from the MDP theory are then applied to detect changes in i.p.i.d. processes. It is shown that while the optimal change point algorithm is a stopping rule based on a periodic sequence of thresholds, a single-threshold policy is asymptotically optimal, as the probability of false alarm goes to zero. Numerical results are provided to demonstrate that the asymptotically optimal policy is not strictly optimal.

I. INTRODUCTION

In the problem of quickest change detection, the objective is to detect a change in the distribution of a sequence of random variables with the minimum possible delay, subject to a constraint on the rate of false alarms [1]–[3]. Optimal or asymptotically optimal algorithms for quickest change detection are available in the literature. The results can be divided broadly into two categories: results for independent and identically distributed (i.i.d.) processes with algorithms that can be computed recursively and using finite memory and enjoy strong optimality properties [4], [5], and results for non-i.i.d. data with algorithms that cannot be necessarily computed recursively or using finite memory but are asymptotically optimal [6]–[9].

In this paper, we develop theory and algorithms for detecting changes in stochastic processes that have periodically varying statistical characteristics. In this non-i.i.d. setting, we will show that the optimal algorithms can be computed recursively and using finite memory. The motivation for this problem

comes from the following anomaly detection problems in cyber-physical systems and biology where such periodic behavior is observed.

- 1) **Traffic monitoring:** In [11] and [12], we reported results on multimodal traffic data we collected from NYC around a 5K run; during, before and after the run. We collected CCTV images, Twitter and Instagram data. We extracted counts of persons and vehicles appearing in CCTV images over time using a deep neural network-based object detector. We observed that in the absence of the event (in the normal regime), the counts have a periodic statistical behavior (over a day or a week) with increased intensity every day during morning and evening rush hours.
- 2) **Social networks:** We also observed in [11] and [12] that the aggregate social network behavior shows periodic characteristics under the normal regime. Also, the total number of Instagram messages posted in a rectangular area around the CCTV cameras showed periodic behavior.
- 3) **Power grid monitoring:** The power usage by end users have a periodic pattern with low usage at nighttime and high usage at daytime [10].
- 4) **Neural spike patterns:** In brain-computer interface studies where single neural spike data is collected, the spike firing pattern can exhibit statistically periodic behavior in the absence of any external stimuli; see, for example, [13].
- 5) **ECG:** Several biological signals including the ECG have a periodic behavior [14].

The problem of anomaly detection in the above-mentioned applications can be seen as a problem of detecting changes in deviation from periodic statistical behavior.

In this paper, we develop a Bayesian theory for anomaly detection in problems where the statistical characteristics are periodic. We introduce a class of stochastic processes called independent and periodically identically distributed (i.p.i.d.) processes that can be used to model such periodic statistical behavior. We then develop algorithms for quickest detection of changes in i.p.i.d. processes and prove their optimality with respect to the Bayesian criterion of Shiryaev [15]. In the Shiryaev formulation, the objective is to detect a change in the distribution of a stochastic process to minimize the average detection delay, subject to a constraint on the probability of false alarm. In the Shiryaev problem, each time we take an observation, we pay a penalty for delay if the change has already occurred. If an alarm is raised and the change has not yet occurred, we pay a penalty for a false alarm. In this paper, we also study a more general or modified Shiryaev formulation where the penalties on the delay and the false alarm are dependent on time. The latter problem is relevant for detecting changes in non-i.i.d. processes. The definition of

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Detection of Changes in Random Processes Laimutis Telksnys, 1986-10-24 **Detection of Changes in Random Processes** L. Tel'ksnis, 1986 Econometrics of Structural Change Walter Krämer, 2012-12-06 Econometric models are made up of assumptions which never exactly match reality Among the most contested ones is the requirement that the coefficients of an econometric model remain stable over time Recent years have therefore seen numerous attempts to test for it or to model possible structural change when it can no longer be ignored This collection of papers from Empirical Economics mirrors part of this development The point of departure of most studies in this volume is the standard linear regression model $Y_t = \alpha + \beta_1 U_t + \epsilon_t$ where notation is obvious and where the index t emphasises the fact that structural change is mostly discussed and encountered in a time series context It is much less of a problem for cross section data although many tests apply there as well The null hypothesis of most tests for structural change is that $\beta_j = \beta_j^0$ for all t i e that the same regression applies to all time periods in the sample and that the disturbances u are well behaved The well known Chow test for instance assumes that there is a single structural shift at a known point in time i e that $\beta_j = \beta_j^0$ for $t \leq t_0$ and $\beta_j = \beta_j^1$ for $t > t_0$ Robust algorithms for detecting a change in a stochastic process with infinite memory P. Papantoni-Kazakos, 1988 The authors present and discuss a class of continuous operations on the family of discrete time stochastic processes which serves as a guide to construct qualitatively robust operations for a given class of processes namely the one induced by a nominal process and a substitutive contaminating process The results are general enough to help develop any robust statistical procedure but the authors have concentrated their attention on detection of a change from one class of processes to another disjoint class of processes while both classes consist of not necessarily Markov processes and satisfy certain mixing conditions in addition to stationarity and ergodicity Two quantitative measures of robustness breakdown point and influence functions are also developed for few examples KR **Monitoring Behavior and Supervisory Control** T. Sheridan, 2013-03-09 This book includes all papers presented at the International Symposium on Monitoring Behavior and Supervisory Control held at Berchtesgaden Federal Republic of Germany March 8-12 1976 The Symposium was sponsored by the Scientific Affairs Division of the North Atlantic Treaty Organization Brussels and the government of the Federal Republic of Germany Bonn We believe the book constitutes an important and timely status report on monitoring behavior and supervisory control by human operators of complex man machine systems in which the computer is sharing key functions with the man These systems include aircraft and other vehicles nuclear and more conventional power plants and processes for the manufacture of chemicals petroleum and discrete parts By monitoring we mean the systematic observation by a human operator of multiple sources of information e g ranging from integrated display consoles to disparate live situations The monitor's purpose is to determine whether operations are normal and proceeding as desired and to diagnose difficulties in the case of abnormality or undesirable outcomes By supervisory control we mean control by a human operator of a computer which at a lower level is controlling a

dynamic system In such systems the computer control normally operates continuously or at high data rates in loops closed through electromechanical sensors and motors By contrast the human operator normally signals or reprograms the computer intermittently or at a much slower pace The human operator handles the higher level tasks and determines the goals of the overall system

Nonparametric Methods in Change Point Problems E. Brodsky, B.S. Darkhovsky, 2013-03-14 The explosive development of information science and technology puts in new problems involving statistical data analysis These problems result from higher requirements concerning the reliability of statistical decisions the accuracy of mathematical models and the quality of control in complex systems A new aspect of statistical analysis has emerged closely connected with one of the basic questions of cybernetics how to compress large volumes of experimental data in order to extract the most valuable information from data observed Detection of large homogeneous segments of data enables one to identify hidden regularities in an object's behavior to create mathematical models for each segment of homogeneity to choose an appropriate control etc Statistical methods dealing with the detection of changes in the characteristics of random processes can be of great use in all these problems These methods have accompanied the rapid growth in data beginning from the middle of our century According to a tradition of more than thirty years we call this sphere of statistical analysis the theory of change point detection During the last fifteen years we have witnessed many exciting developments in the theory of change point detection New promising directions of research have emerged and traditional trends have flourished anew Despite this most of the results are widely scattered in the literature and few monographs exist A real need has arisen for up to date books which present an account of important current research trends one of which is the theory of non parametric change point detection

Analytical Network and System Administration Mark Burgess, 2012-12-17 Network and system administration usually refers to the skill of keeping computers and networks running properly But in truth the skill needed is that of managing complexity This book describes the science behind these complex systems independent of the actual operating systems they work on It provides a theoretical approach to systems administration that saves time in performing common system administration tasks allows safe utilization of untrained and trained help in maintaining mission critical systems allows efficient and safe centralized network administration Managing Human Computer Networks Will show how to make informed analyses and decisions about systems how to diagnose faults and weaknesses Gives advice guidance as to how to determine optimal policies for system management Includes exercises that illustrate the key points of the book The book provides a unique approach to an old problem and will become a classic for researchers and graduate students in Networking and Computer Science as well as practicing system managers and system administrators

Advances in Computer Science for Engineering and Education IV Zhengbing Hu, Sergey Petoukhov, Ivan Dychka, Matthew He, 2021-07-21 This book comprises high quality refereed research papers presented at the Fourth International Conference on Computer Science Engineering and Education Applications ICCSEEA2021 held in Kyiv Ukraine on January 23 24 2021 organized jointly by the

National Technical University of Ukraine Igor Sikorsky Kyiv Polytechnic Institute National Aviation University and the International Research Association of Modern Education and Computer Science The topics discussed in the book include state of the art papers in computer science artificial intelligence engineering techniques genetic coding systems deep learning with its medical applications and knowledge representation with its applications in education It is an excellent source of references for researchers graduate students engineers management practitioners and undergraduate students interested in computer science and their applications in engineering and education

Transactions of the ... Prague Conference on Information Theory, Statistical Decision Functions, Random Processes Conference on Information Theory, Statistical Decision Functions, Random Processes, 1982

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

Current Index to Statistics, Applications, Methods and Theory, 1999 The Current Index to Statistics CIS is a bibliographic index of publications in statistics probability and related fields

FUSION ..., 2000

Analysis and Optimization of Systems Alain Bensoussan, Jacques-Louis Lions, 1984

2002 IEEE International Symposium on Information Theory, 2002

Proceedings, 1995

Multivariate Total Quality Control Carlo Lauro, 2002 The major focus of the book is on using the methods suitable for an on line and off line process control both in the univariate and multivariate case The authors do not only concentrate on the standard situation when the errors accompanying the observed process are normally distributed but also describe in detail the more general situations that call for the use of the robust and non parametric approaches Within these approaches the use of recent methods of the multivariate analysis in the total quality control is enhanced with particular reference to the customer satisfaction area the monitoring of interval data and the comparison of patterns generated from multioccasion observations The authors cover both practical computational aspects of the problem and the necessary mathematical background taking into account requirements of total quality control

Statistical Theory and Method Abstracts, 1999

Proceedings of the ... Conference on Information Sciences and Systems, 1988

An algorithm for detecting changes in battle scenaria Panos V. Kazakos, 1987 In distributed tactical decision making commanders make decisions based on data generated by their local territory as well as on decisions and information communicated to them by other commanders The timely aspect of the decisions is controlled by the rate with

which the commanders receive data which is in turn controlled by the deployed transmission algorithms The accuracy of the decisions on the other hand depends heavily on the way that the decision makers perceive their environment This perception corresponds to a number of alternative models where the latter are a priori developed based on the various battle scenarios Each such model is associated with an appropriate decision mode Furthermore a model or battle scenario may shift to another such model at a random time In the event of such a shift it is thus crucial that the commander be alerted for adaptation to the appropriate decision mode In this paper we describe an algorithm which can be deployed in an automatic fashion to alert the commanders about changes in battle scenarios

Journal of the American Statistical Association, 2007 A scientific and educational journal not only for professional statisticians but also for economists business executives research directors government officials university professors and others who are seriously interested in the application of statistical methods to practical problems in the development of more useful methods and in the improvement of basic statistical data

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