Recent Trends on Nonlinear Filtering for Inverse Problems

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Abstract

Among the class of nonlinear particle filtering methods, the Ensemble Kalman Filter (EnKF) has gained recent attention for its use in solving inverse problems. We review the original method and discuss recent developments in particular in view of the limit for infinitely particles and extensions towards stability analysis and multi–objective optimization. We illustrate the performance of the method by using test inverse problems from the literature.

Keywords: Ensemble Kalman inversion, nonlinear filtering methods, inverse problems, multi-objective optimization, stability analysis

AMS subject classification: 65N21, 93E11, 35Q93, 37K35

1. Introduction

This review paper focuses on the Ensemble Kalman Filter applied to general inverse problems. In this context, some literature also uses the term Ensemble Kalman Inversion (EKI). Solving inverse problems or identification problems means determining parameters of a given model in order to obtain observable data. Due to the large range of applications, several approaches have been proposed in the literature to solve inverse problems. For instance, some well-known techniques rely on Bayesian formulation [1], but they can be extremely expensive. For this reason, efficient numerical schemes to solve the Bayesian inversion have been studied [2–4].

In this paper we are interested in solving inverse problems using a classical approach, i.e. relying on an optimization viewpoint, and in the numerical solution via the so-called particle methods. These can be divided into two classes of methods: the ones coming from particle swarm optimization, e.g. see [5] and the references therein, and the ensemble Kalman methods.

The EKI method belongs indeed to the class of particle methods and it is an iterative method for solving inverse problems. The method was originally introduced in [6] for unconstrained minimization problems, and recently extended also to the presence of different types of constraints [7–9]. The original EnKF has already been introduced more than ten years ago [10–13] as a discrete time method to estimate state variables and parameters of stochastic dynamical systems. The EKI method has become popular recently, because of the fact that it does not require derivatives of the underlying model for optimization but at the same time enjoys provable convergence results. Applications have been so far, in particular, in oceanography [14], reservoir modeling [15], weather forecasting [16], milling process [17], process control [18], geophysical applications [19–21], physics [22] and also machine learning [23–25]. The literature on Kalman filtering is very rich and we can not review this in detail here, but refer to the reference for further details. Our focus is on the reformulation of the EnKF for solving inverse problems as outlined below, in Section 1.2.

1.1. *Formulation of the ensemble Kalman inversion*

In order to present the mathematical formulation of the EKI method, we denote by $\mathcal{G} : X \to Y$ the given (nonlinear) forward operator between finite dimensional Hilbert spaces $X = \mathbb{R}^d$, $d \in \mathbb{N}$, and

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Recent Trends in Nonlinear Analysis Alfonso Vignoli,Jürgen Appell,2000 *Recent Trends in Nonlinear Analysis* Jürgen Appell,2012-10-23 The book contains a collection of 21 original research papers which report on recent developments in various fields of nonlinear analysis The collection covers a large variety of topics ranging from abstract fields such as algebraic topology functional analysis operator theory spectral theory analysis on manifolds partial differential equations boundary value problems geometry of Banach spaces measure theory variational calculus and integral equations to more application oriented fields like control theory numerical analysis mathematical physics mathematical economy and financial mathematics The book is addressed to all specialists interested in nonlinear functional analysis and its applications but also to postgraduate students who want to get in touch with this important field of modern analysis It is dedicated to Alfonso Vignoli who has essentially contributed to the field on the occasion of his sixtieth birthday **Trends in Nonlinear Analysis** Markus Kirkilionis,Susanne Krömker,Rolf Rannacher,Friedrich Tomi,2013-04-17 Applied mathematics is a central connecting link between scientific observations and their theoretical interpretation Nonlinear analysis has surely contributed major developments which nowadays shape the face of applied mathematics At the beginning of the millennium all sciences are expanding at increased speed Technological ecological economical and medical problem solving is a central issue of every modern society Mathematical models help to expose fundamental structures hidden in these problems and serve as unifying tools to deepen our understanding What are the new challenges applied mathematics has to face with the increased diversity of scientific problems In which direction should the classical tools of nonlinear analysis be developed further How do new available technologies influence the development of the field How can problems be solved which have been beyond reach in former times It is the aim of this book to explore new developments in the field by way of discussion of selected topics from nonlinear analysis Current Trends in Mathematical Analysis and Its Interdisciplinary Applications Hemen Dutta,Ljubiša D. R. Kočinac,Hari M. Srivastava,2019-08-23 This book explores several important aspects of recent developments in the interdisciplinary applications of mathematical analysis MA and highlights how MA is now being employed in many areas of scientific research Each of the 23 carefully reviewed chapters was written by experienced expert s in respective field and will enrich readers understanding of the respective research problems providing them with sufficient background to understand the theories methods and applications discussed The book s main goal is to highlight the latest trends and advances equipping interested readers to pursue further research of their own Given its scope the book will especially benefit graduate and PhD students researchers in the applied sciences educators and engineers with an interest in recent developments in the interdisciplinary applications of mathematical analysis **New Trends in Applied Analysis and Computational Mathematics** Susanta Kumar Paikray,Hemen Dutta,John N. Mordeson,2021-06-28 The volume contains original research papers as the Proceedings of the International Conference on Advances in Mathematics and

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researcher and teacher with vision and dedication The present volume is dedicated to the memory of Brunello Terreni His mathematical interests are reflected in 20 expository articles written by distinguished mathematicians The unifying theme of the articles is evolution equations and functional analysis which is presented in various and diverse forms parabolic equations semigroups stochastic evolution optimal control existence uniqueness and regularity of solutions inverse problems as well as applications Contributors P Acquistapace V Barbu A Briani L Boccardo P Colli Franzone G Da Prato D Donatelli A Favini M Fuhrmann M Grasselli R Illner H Koch R Labbas H Lange I Lasiecka A Lorenzi A Lunardi P Marcati R Nagel G Nickel V Pata M M Porzio B Ruf G Savar R Schnaubelt E Sinestrari H Tanabe H Teismann E Terraneo R Triggiani A Yagi

   Hyperfinite Dirichlet Forms and Stochastic Processes Sergio Albeverio,Ruzong Fan,Frederik S. Herzberg,2011-05-27 This monograph treats the theory of Dirichlet forms from a comprehensive point of view using nonstandard analysis Thus it is close in spirit to the discrete classical formulation of Dirichlet space theory by Beurling and Deny 1958 The discrete infinitesimal setup makes it possible to study the diffusion and the jump part using essentially the same methods This setting has the advantage of being independent of special topological properties of the state space and in this sense is a natural one valid for both finite and infinite dimensional spaces The present monograph provides a thorough treatment of the symmetric as well as the non symmetric case surveys the theory of hyperfinite L vy processes and summarizes in an epilogue the model theoretic genericity of hyperfinite stochastic processes theory **Flow Lines and Algebraic Invariants in Contact Form Geometry** Abbas Bahri,2012-12-06 This text features a careful treatment of flow lines and algebraic invariants in contact form geometry a vast area of research connected to symplectic field theory pseudo holomorphic curves and Gromov Witten invariants contact homology In particular this work develops a novel algebraic tool in this field rooted in the concept of critical points at infinity the new algebraic invariants defined here are useful in the investigation of contact structures and Reeb vector fields The book opens with a review of prior results and then proceeds through an examination of variational problems non Fredholm behavior true and false critical points at infinity and topological implications An increasing convergence with regular and singular Yamabe type problems is discussed and the intersection between contact form and Riemannian geometry is emphasized with a specific focus on a unified approach to non compactness in both disciplines Fully detailed explicit proofs and a number of suggestions for further research are provided throughout Rich in open problems and written with a global view of several branches of mathematics this text lays the foundation for new avenues of study in contact form geometry Graduate students and researchers in geometry partial differential equations and related fields will benefit from the book s breadth and unique perspective *Nonlinear Phenomena in Mathematical Sciences* V. Lakshmikantham,2014-05-12 Nonlinear Phenomena in Mathematical Sciences contains the proceedings of an International Conference on Nonlinear Phenomena in Mathematical Sciences held at the University of Texas at Arlington on June 16 20 1980 The papers explore trends in nonlinear phenomena in mathematical sciences with emphasis on nonlinear functional

analytic methods and their applications nonlinear wave theory and applications to medical and life sciences In the area of nonlinear functional analytic methods and their applications the following subjects are discussed optimal control theory periodic oscillations of nonlinear mechanical systems Leray Schauder degree theory differential inequalities applied to parabolic and elliptic partial differential equations bifurcation theory stability theory in analytical mechanics singular and ordinary boundary value problems etc The following topics in nonlinear wave theory are considered nonlinear wave propagation in a randomly homogeneous media periodic solutions of a semilinear wave equation asymptotic behavior of solutions of strongly damped nonlinear wave equations shock waves and dissipation theoretical methods for a nonlinear Schr dinger equation and nonlinear hyperbolic Volterra equations occurring in viscoelasticity Applications to medical and life sciences include mathematical modeling in physiology pharmacokinetics and neuro mathematics along with epidemic modeling and parameter estimation techniques This book will be helpful to students practitioners and researchers in the field of mathematics *Systems of Conservation Laws* Yuxi Zheng,2012-12-06 This work should serve as an introductory text for graduate students and researchers working in the important area of partial differential equations with a focus on problems involving conservation laws The only requisite for the reader is a knowledge of the elementary theory of partial differential equations Key features of this work include broad range of topics from the classical treatment to recent results dealing with solutions to 2D compressible Euler equations good review of basic concepts 1 D Riemann problems concrete solutions presented with many examples over 100 illustrations open problems and numerical schemes numerous exercises comprehensive bibliography and index appeal to a wide audience of applied mathematicians graduate students physicists and engineers Written in a clear accessible style the book emphasizes more recent results that will prepare readers to meet modern challenges in the subject that is to carry out theoretical numerical and asymptotical analysis <u>Carleman Estimates and Applications to Uniqueness and Control Theory</u> Feruccio Colombini,Claude Zuily,2012-12-06 The articles in this volume reflect a subsequent development after a scientific meeting entitled Carleman Estimates and Control Theory held in Cartona in September 1999 The 14 research level articles written by experts focus on new results on Carleman estimates and their applications to uniqueness and controlla bility of partial differential equations and systems The main topics are unique continuation for elliptic PDEs and systems con trol theory and inverse problems New results on strong uniqueness for second or higher order operators are explored in detail in several papers In the area of control theory the reader will find applications of Carleman estimates to stabiliza tion observability and exact control for the wave and the SchrOdinger equations A final paper presents a challenging list of open problems on the topic of control lability of linear and sernilinear heat equations The papers contain exhaustive and essentially self contained proofs directly ac cessible to mathematicians physicists and graduate students with an elementary background in PDEs Contributors are L Aloui M Bellassoued N Burq F Colombini B Dehman C Grammatico M Khenissi H Koch P Le Borgne N Lerner T Nishitani T Okaji K D Phung R Regbaoui X

Saint Raymond D Tataru and E Zuazua   **Spatial Patterns** L.A. Peletier,W.C. Troy,2012-12-06 The study of spatial patterns in extended systems and their evolution with time poses challenging questions for physicists and mathematicians alike Waves on water pulses in optical fibers periodic structures in alloys folds in rock formations and cloud patterns in the sky patterns are omnipresent in the world around us Their variety and complexity make them a rich area of study In the study of these phenomena an important role is played by well chosen model equations which are often simpler than the full equations describing the physical or biological system but still capture its essential features Through a thorough analysis of these model equations one hopes to glean a better under standing of the underlying mechanisms that are responsible for the formation and evolution of complex patterns Classical model equations have typically been second order partial differential equations As an example we mention the widely studied Fisher Kolmogorov or Allen Cahn equation originally proposed in 1937 as a model for the interaction of dispersal and fitness in biological populations As another example we mention the Burgers equation proposed in 1939 to study the interaction of diffusion and nonlinear convection in an attempt to understand the phenomenon of turbulence Both of these are nonlinear second order diffusion equations   Partial Differential Equations and Mathematical Physics Kunihiko Kajitani,Jean Vaillant,2002-12-13 The 17 invited research articles in this volume all written by leading experts in their respective fields are dedicated to the great French mathematician Jean Leray A wide range of topics with significant new results detailed proofs are presented in the areas of partial differential equations complex analysis and mathematical physics Key subjects are Treated from the mathematical physics viewpoint nonlinear stability of an expanding universe the compressible Euler equation spin groups and the Leray Maslov index Linked to the Cauchy problem an intermediate case between effective hyperbolicity and the Levi condition global Cauchy Kowalewski theorem in some Gevrey classes the analytic continuation of the solution necessary conditions for hyperbolic systems well posedness in the Gevrey class uniformly diagonalizable systems and reduced dimension and monodromy of ramified Cauchy problem Additional articles examine results on Local solvability for a system of partial differential operators The hypoellipticity of second order operators Differential forms and Hodge theory on analytic spaces Subelliptic operators and sub Riemannian geometry Contributors V Ancona R Beals A Bove R Camales Y Choquet Bruhat F Colombini M De Gosson S De Gosson M Di Flaviano B Gaveau D Gourdin P Greiner Y Hamada K Kajitani M Mechab K Mizohata V Moncrief N Nakazawa T Nishitani Y Ohya T Okaji S Ouchi S Spagnolo J Vaillant C Wagschal S Wakabayashi The book is suitable as a reference text for graduate students and active researchers   New Advances in Mechanisms, Mechanical Transmissions and Robotics Erwin-Christian Lovasz,Inocentiu Maniu,Ioan Doroftei,Mircea Ivanescu,Corina-Mihaela Gruescu,2020-10-14 This volume gathers the proceedings of the Joint International Conference of the XIII International Conference on Mechanisms and Mechanical Transmissions MTM and the XXIV International Conference on Robotics Robotics held in Timi oara Romania It addresses the applications of mechanisms and transmissions in several modern technical fields such as mechatronics

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forcing period doubling twisted orbits first integrals gradients etc Periodic solutions of Hamiltonian systems in particular spring pendulum systems are studied as well as Hopf bifurcation for all these situations

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