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 $\mathcal{G} : X \rightarrow Y$ 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,2012-12-06 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 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 Computing held at Veer Surendra Sai University of Technology Odisha India on 7 8 February 2020 It focuses on new trends in applied analysis computational mathematics and related areas It also includes certain new models image analysis technique fluid flow problems etc as applications of mathematical analysis and computational mathematics The volume should bring forward new and emerging topics of mathematics and computing having potential applications and uses in other areas of sciences It can serve as a valuable resource for graduate students researchers and educators interested in mathematical tools and techniques for solving various problems arising in science and engineering **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 experts 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   <u>New Trends in Analysis and Interdisciplinary Applications</u> Pei Dang,Min Ku,Tao Qian,Luigi G. Rodino,2017-04-18 This book presents a collection of papers from the 10th ISAAC Congress 2015 held in Macau China The papers prepared by respected international experts address recent results in Mathematics with a special focus on Analysis By structuring the content according to the various mathematical topics the volume offers specialists and non specialists alike an excellent source of information on the state of the art in Mathematical Analysis and its interdisciplinary applications   **Variational Problems in Riemannian Geometry** Paul Baird,Ahmad El Soufi,Ali Fardoun,Rachid Regbaoui,2012-12-06 This book collects invited contributions by specialists in the domain of elliptic partial differential equations and geometric flows There are introductory survey articles as well as papers presenting the latest research results Among the topics covered are blow up theory for second order elliptic equations bubbling phenomena in the harmonic map heat flow applications of scans and fractional power integrands heat flow for the p energy functional Ricci flow and evolution by curvature of networks of curves in the plane   *Evolution Equations, Semigroups and Functional Analysis* Alfredo Lorenzi,Bernhard Ruf,2012-12-06 Brunello Terreni 1953 2000 was a 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   *Latest Trends in Engineering and Technology* Sajjan Singh,Sarabpreet Kaur,2024-06-28 We are very pleased to introduce the proceedings of the International Conference on Latest Trends in Engineering and Technology ICLTET 2023 Papers were well presented in the conference in the fields of Artificial Intelligence Machine learning IOT Communication Networks Mechanical Engineering Civil Engineering Nano Material Research Business Management and many more to arouse a high level of interest The presented papers maintained the high promise suggested by the written abstracts and the program was chaired in a professional and efficient way by the session chair who were selected for their expertise in the subject The number of

delegates was also highly gratifying showing the high level of interest in the subject This Proceeding provides the permanent record of what was presented They indicate the state of development at the time of writing of all aspects of this important topic and will be invaluable to all academicians and researchers in the field for that reason Finally it is appropriate that we record our thanks to our fellow members of the Technical Organizing Committee for encouraging participation from those areas We are also indebted to those who served as session chair and reviewers without their support the conference could not have been the success that it was We also acknowledge the authors themselves without whose expert input there would have been no conference Their efforts made a great contribution to its success **Carleman Estimates and Applications to Uniqueness and Control Theory** 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   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 **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

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

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equations the discussions focus on nonlinear oscillations rotating spiral waves stability and asymptotic behavior discrete time models in population genetics and predator prey systems In optimization theory the following topics are considered inverse and ill posed problems with application to geophysics conjugate gradients and quasi Newton methods with applications to large scale optimization sequential conjugate gradient restoration algorithm for optimal control problems with non differentiable constraints differential geometric methods in nonlinear programming and equilibria in policy formation games with random voting In the area of constructive techniques in numerical analysis numerical and approximate solutions of boundary value problems for ordinary and partial differential equations are examined along with finite element analysis and constructive techniques for accretive and monotone operators In addition the book explores turbulent fluid flows stability problems for Hopf bifurcation product integral representation of Volterra equations with delay weak solutions of variational problems nonlinear integration on measures and fixed point theory This monograph will be helpful to students practitioners and researchers in the field of mathematics   Equivariant Degree Theory Jorge Ize,Alfonso Vignoli,2008-08-22 This book presents a new degree theory for maps which commute with a group of symmetries This degree is no longer a single integer but an element of the group of equivariant homotopy classes of maps between two spheres and depends on the orbit types of the spaces The authors develop completely the theory and applications of this degree in a self contained presentation starting with only elementary facts The first chapter explains the basic tools of representation theory homotopy theory and differential equations needed in the text Then the degree is defined and its main abstract properties are derived The next part is devoted to the study of equivariant homotopy groups of spheres and to the classification of equivariant maps in the case of abelian actions These groups are explicitly computed and the effects of symmetry breaking products and composition are thorougly studied The last part deals with computations of the equivariant index of an isolated orbit and of an isolated loop of stationary points Here differential equations in a variety of situations are considered symmetry breaking 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   *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 biomechanics machines micromachines robotics and apparatus In doing so it combines theoretical findings and experimental testing The book presents peer reviewed papers written by researchers specialized in mechanism analysis and synthesis dynamics of mechanisms and machines mechanical transmissions biomechanics precision mechanics mechatronics micromechanisms and microactuators computational and

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Table of Contents Recent Trends In Nonlinear Analysis

1. Understanding the eBook Recent Trends In Nonlinear Analysis
   - The Rise of Digital Reading Recent Trends In Nonlinear Analysis
   - Advantages of eBooks Over Traditional Books
2. Identifying Recent Trends In Nonlinear Analysis
   - Exploring Different Genres
   - Considering Fiction vs. Non-Fiction
   - Determining Your Reading Goals
3. Choosing the Right eBook Platform
   - Popular eBook Platforms
   - Features to Look for in an Recent Trends In Nonlinear Analysis
   - User-Friendly Interface
4. Exploring eBook Recommendations from Recent Trends In Nonlinear Analysis
   - Personalized Recommendations

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