

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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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

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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 understanding 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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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 thoroughly 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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