

# Recent Trends on Nonlinear Filtering for Inverse Problems

Michael Herty<sup>1\*</sup>, Elisa Iacomini<sup>1</sup>, Giuseppe Visconti<sup>2</sup>

<sup>1</sup>Institute for Geometry and Applied Mathematics, RWTH Aachen University, Tempelgraben 55, 52064 Aachen, Germany

<sup>2</sup>Department of Mathematics, Sapienza University of Rome, P.le Aldo Moro 5, 00185 Rome, Italy

\*Email address for correspondence: [herty@igpm.rwth-aachen.de](mailto:herty@igpm.rwth-aachen.de)

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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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*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 controllability of partial differential equations and systems The main topics are unique continuation for elliptic PDEs and systems control 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 stabilization observability and exact control for the wave and the Schrödinger equations A final paper presents a challenging list of open problems on the topic of controllability of linear and semilinear heat equations The papers contain exhaustive and essentially self contained proofs directly accessible 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 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 Differential forms and Hodge theory on analytic spaces

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**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 experimental methods CAD in mechanism and machine design mechanical design of robot architecture parallel robots mobile



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