

Adaptive Finite Element Methods for Optimal Control of Partial Differential Equations: Basic Concept

R. Becker, H. Kapp, R. Rannacher¹

Summary. We develop a new approach towards error control and adaptivity for finite element discretizations in optimization problems governed by partial differential equations. Using the Lagrangian formalism the goal is to compute stationary points of the first-order necessary optimality conditions. The mesh adaptation is driven by residual-based *a posteriori* error estimates derived by duality arguments. This approach facilitates control of the error with respect to any given quantity of physical interest. The specific feature introduced by the optimization problem is the natural choice of the error-control functional to coincide with the cost functional of the optimization problem. In this case, the Lagrangian multiplier can directly be used in weighting the cell-residuals in the error estimator. This leads to a particularly simple and cost-efficient algorithm for adapting the mesh according to the particular needs of the optimization problem. This approach is developed and tested for simple model problems in optimal control of semiconductivity.

1 Introduction

In this article we develop an adaptive finite element method for optimal control problems governed by elliptic partial differential equations. The main goal is the derivation of *a posteriori* error estimates as basis for controlling the discretization error. Therefore, we begin our analysis for a simple model problem with a linear state equation. The control acts on a part of the boundary and aims to minimize a quadratic cost functional which involves observations on a possibly different part of the boundary. Despite its simplicity, this problem represents the main structure of optimal control and is chosen in order to clarify the idea underlying the proposed procedure.

The control problem is first described in the continuous setting and the Euler-Lagrange equations are formulated using the classical framework of Lions [5]. This leads to a system of coupled partial differential equations for the state variable u , the control variable q , and the Lagrangian multiplier λ . This system has the usual saddle point structure and admits a unique solution under natural conditions. We use a standard finite element discretization of the Euler-Lagrange system. This implies that the set of admissible solutions is also discretized and therefore differs from the continuous one. As long as the discretization procedure uses pure Galerkin techniques the discrete problem actually corresponds to a formulation of the original minimization problem on the discrete space. Since discretization in partial differential equations is expensive, at least for praxis-relevant models, the question of how they affect the quality of the optimization result is crucial for an economical computation. The need for adaptive error control is therefore evident.

For *a posteriori* error estimation, we apply the general error-control approach developed in [2] for finite-element Galerkin discretizations of partial differential equations. In this method a

¹This work has been supported by the German Research Foundation (DFG), SFB 359 Reactive Flows, Diffusion and Transport, Institute of Applied Mathematics, University of Heidelberg, INF 293, D-69120 Heidelberg, Germany, E-mail: numerik@wr.uni-heidelberg.de, Internet: <http://gaia.iwr.uni-heidelberg.de>

Adaptive Finite Element Methods For Differential Equations

Joacim Rocklöv



Adaptive Finite Element Methods For Differential Equations:

Adaptive Finite Element Methods for Differential Equations Wolfgang Bangerth, Rolf Rannacher, 2003-01-23 The key issues are a posteriori error estimation and its automatic mesh adaptation Besides the traditional approach of energy norm error control a new duality based technique the Dual Weighted Residual method for goal oriented error estimation is discussed in detail This method aims at economical computation of arbitrary quantities of physical interest by properly adapting the computational mesh This is typically required in the design cycles of technical applications For example the drag coefficient of a body immersed in a viscous flow is computed then it is minimized by varying certain control parameters and finally the stability of the resulting flow is investigated by solving an eigenvalue problem Goal oriented adaptivity is designed to achieve these tasks with minimal cost At the end of each chapter some exercises are posed in order to assist the interested reader in better understanding the concepts presented Solutions and accompanying remarks are given in the Appendix

Adaptive Finite Element Methods for Differential Equations Wolfgang Bangerth, Rolf Rannacher, 2003

Adaptive Finite Element Methods for Differential Equations Wolfgang Bangerth, Rolf Rannacher, 2014-03-12 These Lecture Notes have been compiled from the material presented by the second author in a lecture series Nachdiplomvorlesung at the Department of Mathematics of the ETH Zurich during the summer term 2002 Concepts of self adaptivity in the numerical solution of differential equations are discussed with emphasis on Galerkin finite element methods The key issues are a posteriori error estimation and automatic mesh adaptation Besides the traditional approach of energy norm error control a new duality based technique the Dual Weighted Residual method or shortly DWR method for goal oriented error estimation is discussed in detail This method aims at economical computation of arbitrary quantities of physical interest by properly adapting the computational mesh This is typically required in the design cycles of technical applications For example the drag coefficient of a body immersed in a viscous flow is computed then it is minimized by varying certain control parameters and finally the stability of the resulting flow is investigated by solving an eigenvalue problem Goal oriented adaptivity is designed to achieve these tasks with minimal cost The basics of the DWR method and various of its applications are described in the following survey articles R Rannacher 114 Error control in finite element computations In Proc of Summer School Error Control and Adaptivity in Scientific Computing H Bulgak and C Zenger eds pp 247 278 Kluwer Academic Publishers 1998 M Braack and R Rannacher 42 Adaptive finite element methods for low Mach number flows with chemical reactions

Adaptive Finite Element Methods for Multiscale Partial Differential Equations Achim Nonnenmacher, Assyr Abdulle (Mathematiker), 2011

Adaptive Finite Element Methods for Time Dependent Partial Differential Equations Slimane Adjerid, 1985

Error-controlled Adaptive Finite Elements in Solid Mechanics Ekkehard Ramm, E. Rank, R. Rannacher, K. Schweizerhof, E. Stein, W. Wendland, G. Wittum, Peter Wriggers, Walter Wunderlich, 2002-12-30 Finite Element Methods are used for numerous engineering applications where numerical solutions

of partial differential equations are needed As computers can now deal with the millions of parameters used in these methods automatic error estimation and automatic adaptation of the utilised method according to this error estimation has become a hot research topic This text offers comprehensive coverage of this new field of automatic adaptation and error estimation bringing together the work of eight outstanding researchers in this field who have completed a six year national research project within the German Science Foundation The result is a state of the art work in true reference style Each chapter is self contained and covers theoretical algorithmic and software presentations as well as solved problems A main feature consists of several carefully elaborated benchmarks of 2D and 3D applications First book to go beyond the Finite Element Method in itself Covers material from a new research area Presents benchmarks of 2D and 3D applications Fits with the new trend for genetic strategies in engineering

Adaptive Finite Element Methods for Optimization in Partial Differential Equations Hartmut Kapp,2000

Error-controlled Adaptive Finite Elements in Solid Mechanics Ekkehard Ramm,E. Rank,R. Rannacher,K. Schweizerhof,E. Stein,W. Wendland,G. Wittum,Peter Wriggers,Walter Wunderlich,2003-08-01 Finite Element Methods are used for numerous engineering applications where numerical solutions of partial differential equations are needed As computers can now deal with the millions of parameters used in these methods automatic error estimation and automatic adaptation of the utilised method according to this error estimation has become a hot research topic This text offers comprehensive coverage of this new field of automatic adaptation and error estimation bringing together the work of eight outstanding researchers in this field who have completed a six year national research project within the German Science Foundation The result is a state of the art work in true reference style Each chapter is self contained and covers theoretical algorithmic and software presentations as well as solved problems A main feature consists of several carefully elaborated benchmarks of 2D and 3D applications First book to go beyond the Finite Element Method in itself Covers material from a new research area Presents benchmarks of 2D and 3D applications Fits with the new trend for genetic strategies in engineering Adaptive Finite Element Methods for Optimal Control of Partial Differential Equations Roland Becker,Hartmut Kapp,Rolf Rannacher,1998 *Adaptive Finite Elements in the Discretization of Parabolic Problems*

Christian A. Möller,2011 Adaptivity is a crucial tool in state of the art scientific computing However its theoretical foundations are only understood partially and are subject of current research This self contained work provides theoretical basics on partial differential equations and finite element discretizations before focusing on adaptive finite element methods for time dependent problems In this context aspects of temporal adaptivity and error control are considered in particular Based on the gained insights a specific adaptive algorithm is designed and analyzed thoroughly Most importantly it is proven that the presented adaptive method terminates within any demanded error tolerance Moreover the developed algorithm is analyzed from a numerical point of view and its performance is compared to well known standard methods Finally it is applied to the real life problem of concrete carbonation where two different discretizations are compared *Adaptive Finite*

Elements in Linear and Nonlinear Solid and Structural Mechanics Erwin Stein, 2007-04-02 This course with 6 lecturers intends to present a systematic survey of recent research results of well known scientists on error controlled adaptive finite element methods in solid and structural mechanics with emphasis to problem dependent concepts for adaptivity error analysis as well as h and p adaptive refinement techniques including meshing and remeshing Challenging applications are of equal importance including elastic and elastoplastic deformations of solids contact problems and thin walled structures Some major topics should be pointed out namely i The growing importance of goal oriented and local error estimates for quantities of interest in comparison with global error estimates based on dual finite element solutions a The importance of the p version of the finite element method in conjunction with parameter dependent hierarchical approximations of the mathematical model for example in boundary layers of elastic plates Hi The choice of problem oriented error measures in suitable norms considering residual averaging and hierarchical error estimates in conjunction with the efficiency of the associated adaptive computations iv The importance of implicit local postprocessing with enhanced test spaces in order to get constant free i.e. absolute not only relative discretization error estimates v The coupling of error controlled adaptive discretizations and the mathematical modeling in related subdomains such as boundary layers The main goals of adaptivity are reliability and efficiency combined with in sight and access to controls which are independent of the applied discretization methods By these efforts new paradigms in Computational Mechanics should be realized namely verifications and even validations of engineering models

Finite Element Methods and Their Applications Zhangxin

Chen, 2005-10-14 The finite element method is one of the major tools used in the numerical solution of partial differential equations This book offers a fundamental and practical introduction to the method its variants and their applications In presenting the material I have attempted to introduce every concept in the simplest possible setting and to maintain a level of treatment that is as rigorous as possible without being unnecessarily abstract The book is based on the material that I have used in a graduate course at Southern Methodist University for several years Part of the material was also used for my seminar notes at Purdue University University of Minnesota and Texas A&M These two methods have been recently developed The adaptive finite element method is considered in Chap 6 The last four chapters are devoted to applications of these methods to solid mechanics Chap 7 fluid mechanics Chap 8 fluid flow in porous media Chap 9 and semiconductor modeling Chap 10

Adaptive Finite Element Methods for the Identification of Distributed Parameters in Partial Differential

Equations Wolfgang Bangerth, 2002 **Adaptive Finite Element Methods for Optimization in Partial Differential Equations**, 2000 A new approach to error control and mesh adaptivity is described for the discretization of optimal control problems governed by elliptic partial differential equations The Lagrangian formalism yields the first order necessary optimality condition in form of an indefinite boundary value problem which is approximated by an adaptive Galerkin finite element method The mesh design in the resulting reduced models is controlled by residual based a posteriori error estimates

These are derived by duality arguments employing the cost functional of the optimization problem for controlling the discretization error. In this case the computed state and co state variables can be used as sensitivity factors multiplying the local cell residuals in the error estimators. This results in a generic and efficient algorithm for mesh adaptation within the optimization process. Applications of the developed method are boundary control problem models governed by Ginzburg Landau equations, superconductivity in semi conductors by Navier Stokes equations and by the Boussinesq viscosity model flow with temperature transport for zero gravitation. Computations with more than 2 million unknowns were performed.

Adaptive Finite Element Methods for Parameter Estimation Problems in Partial Differential Equations Tao Feng, Mittuniversitetet, 2005 **Accuracy Estimates and Adaptive Refinements in Finite Element Computations** Ivo Babuška, 1986. This book contains papers discussing the recent developments in adaptive methods and their applications in an area of finite elements methods applicable to the needs of civil engineering. Topics covered range from an exposition of basic theory and techniques to detailed discussions of specific applications. Adaptive approaches and the computer assessment of the reliability of the results obtained are also examined. *Adaptive Finite Element Methods for Parabolic Partial Differential Equations* J. E. Flaherty, J. M. Coyle, R. Ludwig, S. F. Davis, 1983. The authors discuss a finite element method for solving initial boundary value problems for vector systems of partial differential equations in one space dimension and time. The method automatically adjusts the computational mesh as the solution evolves in time so as to approximately minimize the local discretization error. They are thus able to calculate accurate solutions with fewer elements than would be necessary with a uniform mesh. This overall method contains two distinct steps: a solution step and a mesh selection step. They solve the partial differential equations using a finite element Galerkin method on trapezoidal space-time elements with either piecewise linear or cubic Hermite polynomial approximations. A variety of mesh selection strategies are discussed and analyzed. Results are presented for several computational examples. **Adaptive Finite Element Methods for the Identification of Distributed Parameters in Partial Differential Equations**, 2002. In this thesis we develop algorithms for the solution of inverse problems by the adaptive finite element method. In particular we consider problems where distributed coefficients in partial differential equations are to be identified from measurements of the state variable. The ingredients for efficient algorithms are error estimates for various quantities such as the misfit or the error in the coefficient and adaptive finite element discretization strategies. We also discuss the numerical solution of the resulting discrete equations as well as the incorporation of inequality constraints on the sought coefficient. The efficiency of the proposed methods is verified at a number of synthetic examples. *Adaptive Finite Element Method IV: Mesh Movement*, 1995. An adaptive finite element method is developed to solve initial boundary value problems for vector systems of parabolic partial differential equations in one space dimension and time. The differential equations are discretized in space using piecewise linear finite element approximations. Superconvergence properties and quadratic polynomials are used to derive a

computationally inexpensive approximation to the spatial component of the error This technique is coupled with time integration schemes of successively higher orders to obtain an approximation of the temporal and total discretization error The stability of several mesh equidistribution schemes for time dependent partial differential equations is studied The schemes move a finite difference or finite element mesh so that a given quantity is uniform over the domain Mesh moving methods that are based on solving a system of ordinary differential equations for the mesh velocities are considered and some of these methods are shown to be unstable with respect to an equidistributing mesh when the partial differential system is dissipative Simple criteria for determining the stability of a particular method are developed and the construction of stable differential systems for the mesh velocities is demonstrated Several examples illustrating stable and unstable mesh motions are present

Control of Coupled Partial Differential Equations Karl Kunisch, Günter Leugering, Jürgen Sprekels, Fredi Tröltzsch, 2007-08-08 The international Conference on Optimal Control of Coupled Systems of partial Differential Equations was held at the Mathematisches Forschungsinstitut Oberwolfach from April 17 to 23 2005 The applications discussed during the conference includes the optimization and control of quantum mechanical systems

Reviewing **Adaptive Finite Element Methods For Differential Equations**: Unlocking the Spellbinding Force of Linguistics

In a fast-paced world fueled by information and interconnectivity, the spellbinding force of linguistics has acquired newfound prominence. Its capacity to evoke emotions, stimulate contemplation, and stimulate metamorphosis is actually astonishing. Within the pages of "**Adaptive Finite Element Methods For Differential Equations**," an enthralling opus penned by a highly acclaimed wordsmith, readers set about an immersive expedition to unravel the intricate significance of language and its indelible imprint on our lives. Throughout this assessment, we shall delve into the book's central motifs, appraise its distinctive narrative style, and gauge its overarching influence on the minds of its readers.

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