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Peter Gruber: Book of Abstracts
Walter Zulehner: Proceedings
Marco Discacciati: Proceedings
Satyendra Tomar: Poster Session

Contents

Part I

Program

08:00 – 09:00	**Breakfast**				
09:00 – 12:30	**Registration**				
12:30 – 13:30	**Lunch**				
	Opening and plenary talks (Chair: Keyes, Location: Bürglsaal and S1)				
14:00 – 14:45	**Kuznetsov:** Domain Decomposition Preconditioners for Anisotropic Diffusion [p. 21]				
14:45 – 15:30	**Adams:** Algebraic multigrid methods for mechanical engineering applications [p. 13]				
15:30 – 16:00	**Coffee break**				
	Minisymposia				
	M06: Multiphysics problems Chair: Kornhuber Location: Bürglsaal	**M05: FETI, balancing, and related hybrid DD methods** Chair: Widlund Location: S1	**M08: Robust methods for multiscale PDE problems** Chair: Scheichl Location: B1	**M10: Time DD methods for evolution problems** Chair: Gander Location: B2	**M01: Advanced multigrid methods for systems of PDEs** Chair: Zikatanov Location: S2
16:00 – 16:25	**Discacciati:** Iterative solution methods for a magnetohydrodynamic problem in velocity-current formulation [p. 47]	**Brenner:** BDDC and FETI-DP without matrices or vectors [p. 41]	**Giraud:** Robust algebraic two-level preconditioner for non-overlapping methods [p. 52]	**Bal:** Symplectic parareal [p. 56]	**Schöberl:** Robust preconditioning in elasticity [p. 32]
16:30 – 16:55	**Omeragic:** Joint electromagnetic-pressure-fluid flow modeling and inversion for oilfield applications [p. 48]	**Mandel:** Multilevel BDDC [p. 43]	**Scherer:** Robust norm equivalencies and optimal preconditioners [p. 53]	**Salomon:** Parareal in time control for quantum systems [p. 57]	**Perrussel:** Algebraic multigrid strategies based on De Rham complexes on graphs with applications to Maxwell's equations [p. 32]
17:00 – 17:25	**Berninger:** On a method of Robin-type for the Richards equation in heterogeneous soil [p. 46]	**Klawonn:** Extending the scalability of FETI-DP: from exact to inexact algorithms [p. 42]	**Graham:** Domain decomposition for multiscale PDEs [p. 52]	**Geiser:** Time- and space-decomposition methods as fast adaptive solvers: theory and applications in fluid dynamics [p. 47]	**Notay:** Two-grid convergence implies unconditionally W-cycle convergence [p. 32]
17:30 – 17:55	**Hoppe:** Modeling and simulation of piezoelectrically agitated acoustic streaming on microfluidic biochips [p. 47]	**Dostal:** Scalable FETI/FETI-DP based algorithms for numerical solution of variational inequalities with dissipative term [p. 41]	**Scheichl:** Robust aggregation-based coarsening for multiscale PDEs [p. 52]	**Schaerer Serra:** Time-parallel iterative algorithms for optimal control of parabolic equations [p. 57]	**Gopalakrishnan:** Multigrid convergence for axisymmetric problems [p. 31]
18:00 – 18:25		**Vondrák:** Scalable FETI algorithms for frictionless contact problems [p. 78]	**Neuss:** Multiscale simulation of diffusion and absorption in chloroplasts [p. 52]	**Lai:** A two-level time domain algorithm for the solution of nonlinear transient parabolic problems with applications [p. 56]	**Vassilevski:** Agglomeration AMGe with local constrained energy minimization interpolation [p. 33]
18:30 – 19:30	**Get Together Dinner**				

Tuesday, July 4

08:00 – 09:00	**Breakfast**				
	Plenary talks (Chair: Quarteroni, Location: Bürglsaal and S1)				
09:00 – 09:45	**Halpern:** Schwarz waveform relaxation algorithms: theory and applications [p. 17]				
09:45 – 10:30	**Kim:** Domain decomposition algorithms for mortar discretizations [p. 19]				
10:30 – 10:50	**Coffee break**				
	Contributed talks				
	Abstract ASM Chair: Steinbach Location: Bürglsaal	**Parallel concepts** Chair: Andjelic Location: S1	hp**-FEM** Chair: Ainsworth Location: B1	**DG + FETI** Chair: Lazarov Location: B2	**DD for applications** Chair: Wheeler Location: S2
10:50 – 11:10	**Dolean:** The relation between optimized Schwarz methods for scalar and systems of partial differential equations [p. 63]	**Haase:** A user friendly toolbox for parallel PDE-solvers [p. 65]	**Melenk:** H-matrix techniques for boundary concentrated FEM [p. 68]	**Kruis:** Reinforcement-matrix interaction modelled by FETI method [p. 66]	**Gerardo-Giorda:** A domain decomposition procedure for the diffusion of an age-structured population in a multi-layer environment [p. 64]
11:15 – 11:35	**Szyld:** Optimal left and right additive Schwarz preconditioning of minimal residual methods with Euclidean and energy norms [p. 72]	**Adolph:** Automatic domain decomposition for a black-box PDE solver [p. 61]	**Eibner:** A multilevel solver for the boundary concentrated FEM. [p. 63]	**Bertoluzza:** The method of mothers for non-overlapping non-matching DDM [p. 61]	**Schädle:** Domain decomposition for Maxwell's equations: scattering off periodic structures [p. 71]
11:40 – 12:00	**Daoud:** Overlapping Schwarz waveform relaxation method for the solution of the forward - backward heat equation. [p. 62]	**Mehl:** Efficient implementation of domain decomposition approaches for the parallel simulation of fluid-structure-interactions [p. 68]	**Pillwein:** Application of computer algebra tools for low energy basis functions [p. 69]	**Krzyzanowski:** Neumann-Neumann method for discontinuous Galerkin Stokes problem [p. 67]	**Toivanen:** Domain decomposition preconditioners for acoustic scattering in layered media [p. 73]
12:05 – 12:25	**Rabanovych:** On the spectra of sums and the norms of products of orthogonal projections [p. 69]	**Vey:** AMDiS - adaptive multidimensional simulations: parallel concepts [p. 73]	**Rapetti:** p-Multigrid for Fekete spectral element method [p. 70]	**Shahbazi:** A high-order discontinuous Galerkin method for the unsteady incompressible Navier-Stokes equations [p. 71]	**Lahmer:** Homogenization techniques in sensor/actuator applications [p. 67]
12:30 – 14:00	**Lunch**				

	Plenary talks (Chair: Bjørstad, Location: Bürglsaal and S1)				
14:00 – 14:45	**Lazarov:** Preconditioning of discontinuous Galerkin FEM of second order elliptic problems [p. 22]				
14:45 – 15:30	**Periaux:** A domain decomposition / Nash equilibrium methodology for the solution of direct and inverse problems in fluid dynamics [p. 25]				
15:30 – 16:00	**Coffee break**				
	Minisymposia				
	M06: Multiphysics problems Chair: Hoppe Location: Bürglsaal	**M05: FETI, balancing, and related hybrid DD methods** Chair: Klawonn Location: S1	**M03: DD in coupled engineering phenomena with multiple scales** Chair: Graham Location: B1	**M04: DD methods motivated by the physics of the underlying problem** Chair: Halpern Location: B2	**M01: Advanced multigrid methods for systems of PDEs** Chair: Vassilevski Location: S2
16:00 – 16:25	**Kaltenbacher:** Advanced coupling of structural mechanics and acoustics in time and frequency domain [p. 48]	**Rheinbach:** FETI-DP and BDDC for higher order methods [p. 44]	**Ewing:** Domain decomposition techniques for treating multi-scale properties in reservoir engineering applications [p. 37]	**Japhet:** Coupling of heterogeneous advection - diffusion problems with an optimized Schwarz waveform relaxation method and nonconforming time discretisation [p. 39]	**Margenov:** CBS constants for graph-Laplacians and application to multilevel methods for discontinuous Galerkin systems [p. 31]
16:30 – 16:55	**Sander:** Multi-dimensional coupling in a human knee model [p. 48]	**Pavarino:** Balancing Neumann-Neumann methods for Fekete spectral elements [p. 44]	**Efendiev:** An adaptive multiscale method for simulation of fluid flow in heterogeneous porous media [p. 37]	**Haynes:** Towards a Schwarz waveform moving mesh solver [p. 39]	**Tomar:** Multilevel preconditioning of elliptic problems discretized by a class of discontinuous Galerkin methods [p. 32]
17:00 – 17:25	**Geiser:** Time-decomposition methods for parabolic problems: convergence results of iterative splitting methods [p. 56]	**Conceicao:** BDD and BDDC preconditioners for stabilized GLS Oseen equations [p. 41]	**Bjørstad:** On the relationship between domain decomposition preconditioners and the multiscale finite volume method [p. 36]	**Santugini:** Challenges of applying domain decompostion methods to micromagnetism [p. 40]	**Kraus:** On the construction of a hierarchical topology with application to algebraic multilevel preconditioning [p. 31]
17:30 – 17:55	**Zunino:** Domain decomposition methods based on weighted interior penalties [p. 49]	**Dryja:** A Neumann-Neumann method for discontinuous Galerkin discretization of elliptic equations [p. 42]	**Rybak:** On a two-level domain decomposition preconditioner for 3D flows in anisotropic highly heterogeneous porous media [p. 37]	**Roux:** Approximate optimal interface conditions for fluid structure coupling in vibro-acoustics [p. 40]	**Zikatanov:** Uniform preconditioning of a generalized finite element method discretizations [p. 33]
18:00 – 18:25		**Of:** An all-floating formulation of the BETI method [p. 43]	**Iliev:** On a two-level domain decomposition preconditioner for 3D Stokes flow in highly complicated geometry [p. 37]	**Szeftel:** Optimized and quasi-optimal Schwarz waveform relaxation for the one dimensional Schrödinger equation [p. 40]	
18:30 – 19:30	**Dinner**				
19:00 – 23:00	**Reception of the invited speakers by the scientific committee**				

08:00 – 09:00	**Breakfast**				
	Plenary talks (Chair: Hoppe, Location: Bürglsaal and S1)				
09:00 – 09:45	**Heinkenschloss:** Domain decomposition methods for PDE constrained optimization [p. 18]				
09:45 – 10:30	**Leugering:** Domain decomposition in optimal control of partial differential equations on networked domains [p. 24]				
10:30 – 10:50	**Coffee break**				
	Contributed talks				
	DD for CFD Chair: Lee Location: Bürglsaal	**Multigrid** Chair: Adams Location: S1	**Optimal control + Inverse** Chair: Heinkenschloss Location: B1	**Aitken-Schwarz DDM** Chair: Gander Location: B2	**Mortaring** Chair: Kim Location: S2
10:50 – 11:10	**Le Borne:** Domain-decomposition based hierarchical matrix preconditioners for the Oseen equations [p. 67]	**Xuejun:** Economical cascadic multigrid method (ECMG) [p. 74]	**Cai:** Fully coupled domain decomposition methods for inverse elliptic problems [p. 62]	**Garbey:** An asynchronous parallel algorithm for the heat equation [p. 64]	**Heinrich:** Nitsche mortaring for some elliptic problems [p. 65]
11:15 – 11:35	**Rapin:** A Neumann-Neumann type algorithm for the Stokes equations using the Smith factorization [p. 70]	**Scacchi:** Multilevel additive Schwarz and multigrid preconditioners for the bidomain system [p. 71]	**Sarkis:** Block matrix preconditioners for elliptic optimal control problems [p. 70]	**Doucet:** On some numerical properties of the Aitken-Schwarz method [p. 63]	**Fallettta:** A mortar finite element method for a heat conduction problem [p. 63]
11:40 – 12:00	**Küttler:** The dilemma of domain decomposition approaches for the interaction of structures and fully enclosed incompressible fluids [p. 67]	**Hubert:** Finite volume method for linear and non linear elliptic problems with discontinuities [p. 66]	**Zulehner:** On Schwarz-type smoothers for saddle point problems with applications to PDE-constrained optimization problems [p. 74]	**Frullone:** Non uniform discrete Fourier transform for adaptive acceleration of the Aitken-Schwarz DDM [p. 64]	**Marcinkowski:** A FETI-DP method for a mortar finite element discretization of fourth order elliptic problems [p. 68]
12:05 – 12:25	**Suzuki:** A balancing Neumann-Neumann solver for Stokes problem and its application to the Earth's mantle convection problem [p. 72]				
12:30 – 13:30	**Lunch**				
13:30 – 19:30	**Excursion**				
19:30 – 20:30	**Dinner**				
20:30 – 22:00	**Business meeting of the scientific committee**				

08:00 – 09:00	**Breakfast**				
	Plenary talks (Chair: Shi, Location: Bürglsaal and S1)				
09:00 – 09:45	**Andjelic:** BEM: Opening the new frontiers in the industrial products design [p. 15]				
09:45 – 10:30	**Steinbach:** Boundary element domain decomposition methods: challenges and applications [p. 26]				
10:30 – 10:50	**Coffee break**				
	Contributed talks				
	DD for BEM Chair: Kuznetsov Location: Bürglsaal	**Software presentation** Chair: Schöberl Location: S1			**DD for mechanics** Chair: Brenner Location: S2
10:50 – 11:10	**Wendland:** Fast boundary element methods for the simulation of electrical eddy current fields, their heat production and cooling [p. 73]	**Gorman:** Parallel anisotropic unstructured mesh optimisation for transient fluid flow problems [p. 65]			**Stals:** Discrete thin plate splines for large data sets [p. 71]
11:15 – 11:35	**Stephan:** Large domain decomposition algorithms for indefinite hypersingular integral equations in three dimensions [p. 72]	**Nagaiah:** Parallel numerical solution of intracellular calcium dynamics [p. 69]			**Guibert:** Schur DDM for stiff DAE/ODE systems for complex mechanical system 0D-modelling [p. 65]
11:40 – 12:30	**Poster Session**				
12:30 – 14:00	**Lunch**				

	Plenary talks (Chair: Kawarada, Location: Bürglsaal and S1)				
14:00 – 14:45	**Ainsworth:** Robustness of some simple smoothers for finite element and boundary elements on nonquasiuniform meshes [p. 14]				
14:45 – 15:30	**Wheeler:** A domain decomposition multiscale mortar mixed method for flow in porous media [p. 27]				
15:30 – 16:00	**Coffee break**				
	Minisymposia				
	M09: Subspace correction methods Chair: Kornhuber Location: Bürglsaal	**M05: FETI, balancing, and related hybrid DD methods** Chair: Dryja Location: S1	**M03: DD in coupled engineering phenomena with multiple scales** Chair: Lazarov Location: B1	**M07: Optimized Schwarz methods: promises and challenges** Chair: Laayouni Location: B2	**M02: DD based on boundary elements** Chair: Steinbach Location: S2
16:00 – 16:25	**Gräser:** Non-smooth Newton methods for set-valued saddle point problems [p. 54]	**Dohrmann:** Algebraic coarse spaces for overlapping Schwarz preconditioners [p. 41]	**Andrä:** Application of domain decomposition methods in micromechanics [p. 36]	**Laayouni:** Optimal and optimized domain decomposition methods for three-dimensional partial differential equations [p. 50]	**Hiptmair:** Resonance free interface coupled BEM for Maxwell's equations [p. 34]
16:30 – 16:55	**Forster:** Fast and reliable pricing of American options with local volatility [p. 54]	**Widlund:** Extending the theory for iterative substructuring algorithms to less regular subdomains [p. 44]	**Ayuso:** Class of preconditioners for discontinuous Galerkin approximations of elliptic problems [p. 36]	**St-Cyr:** Performance of optimized Schwarz in a massively parallel next generation climate model [p. 51]	**Pechstein:** Coupled FETI/BETI solvers for nonlinear potential problems in unbounded regions [p. 35]
17:00 – 17:25	**Hu:** A new kind of multilevel preconditioner for interface operator arising from domain decomposition [p. 54]	**Flemisch:** Efficient solution strategies for coupled problems in acoustics [p. 42]	**Gopalakrishnan:** A hybridization approach to coupling methods [p. 37]	**Dubois:** Optimized Schwarz methods for problems with discontinuous coefficients [p. 50]	**Bouchala:** Scalable BETI based algorithms for numerical solution of variational inequalities [p. 34]
17:30 – 17:55	**Zheng:** An adaptive multilevel method for time-harmonic Maxwell equations with singularities [p. 55]	**Xavier:** FETI-H approach for coupling finite elements and boundary elements in acoustics [p. 44]		**Dolean:** A new domain decomposition method for the compressible Euler equations [p. 50]	**Yu:** The natural boundary reduction and the domain decomposition methods in unbounded domains [p. 35]
18:00 – 18:25	**Hiptmair:** Auxiliary Space Preconditioning in $H(\text{curl})$ [p. 54]	**Magoulès:** Improved ad hoc interface conditions for the FETI domain decomposition method tuned to highly heterogeneous media [p. 42]		**Qaddouri:** Optimized Schwarz method with the Yin-Yang grid for the Shallow-Water Equations [p. 51]	**Litvinenko:** $\mathcal{H}$-matrix based preconditioner for the skin problem [p. 34]
18:30 – 19:00	**Poster Session**				
19:00 – 22:00	**Conference Dinner**				

08:00 – 09:00	**Breakfast**				
	Plenary talks (Chair: Kornhuber, Location: Bürglsaal and S1)				
09:00 – 09:45	**Lee:** Convergence theories of the subspace correction methods for singular and nearly singular system of equations [p. 23]				
09:45 – 10:30	**Krause:** On the multiscale solution of constrained problems in linear elasticity [p. 20]				
10:30 – 10:50	**Coffee break**				
	Contributed talks				
	DD for applications Chair: Leugering Location: Bürglsaal	**Time dependent problems + boundaries** Chair: Halpern Location: S1	**Abstract ASM** Chair: Krause Location: B1	**DD for CFD** Chair: Periaux Location: B2	hp-**FEM + boundaries** Chair: Glowinski Location: S2
10:50 – 11:10	**Kako:** Numerical method for wave propagation problem by FDTD method with PML [p. 66]	**Maday:** Notion of coarse propagators in the parareal algorithm [p. 68]	**Sassi:** Generalization of Lions' nonoverlapping domain decomposition method for contact problems [p. 70]	**Garbey:** Toward a self adaptive multi-algorithm solver for parallel CFD [p. 64]	**Achdou:** Boundary value problems in some ramified domains with a fractal boundary. Transparent boundary conditions [p. 61]
11:15 – 11:35		**Turinici:** Parareal in time control for quantum systems [p. 73]	**Badea:** Additive multilevel Schwarz method for the constrained minimization of functionals in reflexive Banach spaces [p. 61]	**Picard:** Versatile framework for solution verification of complex PDE [p. 69]	**Korneev:** Domain decomposition algorithm for discretizations of 3-d elliptic equations by spectral elements [p. 66]
	Closing and plenary talk (Chair: Widlund, Location: Bürglsaal and S1)				
11:45 – 12:30	**Gander:** Time domain decomposition methods [p. 16]				
12:30 – 14:00	**Lunch**				
13:30 – 19:30	**Departure or individual sightseeing**				
19:30 – 20:30	**Dinner**				

Part II

Abstracts of Invited Talks

Mark Adams

Algebraic multigrid methods for mechanical engineering applications

Location: Bürglsaal **Date:** Monday, July 3, 14:45 – 15:30

An overview of the algorithms that are deployed in the linear solver package Prometheus (available in PETSc) is presented. This includes an introduction to the primary algebraic multigrid method available in Prometheus, smoothed aggregation, as well as details of pertinent algorithmic components such as smoothers that go into a complete multigrid solver. Special attention is paid to the algorithm contributions of the author but a comprehensive overview is presented.

Application of this core linear solver engine to mechanics problems such as tires, an aircraft carrier and micro CT bone modeling problems. Efficient solves (about two minutes per linear solve) of large scale geometric nonlinear problems are presented with over on half billion degrees of freedom. Additionally, this core solution method will be extended to non positive matrices that arise from contact problems and frequency domain analysis.

Mark Ainsworth

Robustness of some simple smoothers for finite element and boundary elements on nonquasiuniform meshes

Location: Bürglsaal **Date:** Thursday, July 6, 14:00 – 14:45

Adaptive finite element and boundary element schemes generally give rise to non - quasiuniform meshes where the ratio of the diameter of the largest to the smallest element in the mesh grows exponentially with the number of adaptive refinement steps. We study the effect on the condition number of the stiffness matrix due to this large global mesh ratio and show that it typically leads to an exponential growth in the condition number. This naturally leads to the question of how one may counteract this effect at minimal cost and to this end, we consider the effect of applying simple point relaxation smoothers and show that, roughly speaking, these serve to remove the ill-effects of a large global mesh ratio for standard nodal finite element bases.

However, this result does not extend to the situation where one uses edge or face finite elements typically employed for the discretisation of problems posed in H(div) and H(curl). We study the conditioning of the resulting stiffness matrices and again show that the matrices are generally rather poorly conditioned due to the large global mesh ratio, and show that simple point relaxation schemes cannot remove this effect. We trace the reason behind this difference and give a simple remedy for curing the problem.

Zoran Andjelic

BEM: Opening the new frontiers in the industrial products design

Location: Bürglsaal **Date:** Thursday, July 6, 09:00 – 09:45

Thanks to the advances achieved in the last several years, BEM became a powerful numerical technique for the industrial products design. Until recent time this technique has been in a praxis recognized as a technique offering from one side some excellent features (2D instead of 3D discretization, treatment of the open-boundary problems, etc.), but from the other side having some serious practical limitations, mostly related to the full-populated, often ill-conditioned matrixes. The new, emerging numerical techniques like MBIT (Multipole-Based Integral Technique), ACA (Adaptive Cross-Approximations), DDT (Domain-Decomposition Technique) seems to bridge some of these known bottlenecks, promoting those the BEM in a high-level tool for even daily-design process of the 3D real-world problems.

The aim of this talk is to illustrate the application of BEM in the design process of the complex industrial products like power transformers or switchgears. We shall discuss some numerical aspects of BEM required to perform a successful simulation of theses devices, preserving both the full physical and geometrical complexity of the problem.

Finally, we shall illustrate how this numerical technique can be used for the simulation of both single-physics problems appearing in the Dielectric Design (Electrostatics) and multi-physics problems in Thermal Design (coupling of Electromagnetic - Heat transfer) and Electro-Mechanical Design (coupling of Electromagnetic - Structural mechanics) problems.

Martin Gander

Time domain decomposition methods

Location: Bürglsaal **Date:** Friday, July 7, 11:45 – 12:30

Time dependent problems are often solved using time marching schemes. Such schemes remain effective on parallel computers as long as each time step is costly enough for an effective parallelization in space. If not, parallelism in time could alleviate the situation, but is it possible to do useful computations at future time steps before the current time step results are known?

I first present a historical overview of algorithms that were proposed over the last 40 years to obtain a certain amount of time parallelism. I will then introduce a general time domain decomposition method based on multiple shooting, which permits the parallel in time computation of solutions of time dependent problems. This time domain decomposition method contains more recent time parallel algorithms like the parareal algorithm. A convergence analysis reveals superlinear convergence of the method on bounded time intervals, and linear convergence on unbounded time intervals under certain conditions. I will illustrate the results with numerical experiments.

LAURENCE HALPERN

Schwarz waveform relaxation algorithms: theory and applications

Location: Bürglsaal **Date:** Tuesday, July 4, 09:00 – 09:45

To solve evolution problems in parallel, many strategies are available: amongst them, implicit time schemes with domain decomposition in space or explicit time schemes with interpolation on the boundary. These two methods have several limitations: in the first case a common time step must be used in each subdomain, while the second case exhibits a lack of stability for hyperbolic problems.

Schwarz Waveform relaxation algorithms develop a completely different strategy: on the continuous level, they compute a solution on each subdomain in space, over the whole time interval, or over time windows. Transmission conditions of differential or integral type on the boundary then transmit the information to the neighbours at the end of the time interval. They are optimized so as to minimize the convergence rate for the interface problem. These algorithms can be used with or without overlap, and thus the discretization can be made independently in the subdomains. This allows for a large versatility: one can deal with large discontinuities in the coefficients, adapt the time step locally, use different numerical methods in different parts of the computational domain, and even different equations and different codes.

In this presentation, I shall give an overview of the algorithms we use, for hyperbolic or parabolic problems. In the parabolic case, a skillful choice of the transmission conditions will allow the convergence rates to be almost independent of the mesh size. In the hyperbolic case, we use absorbing boundary conditions with overlap, and optimize the coefficients. I shall also show how this method produces a "natural" mesh refinement in time and space. Each case is illustrated with numerical experiments.

Matthias Heinkenschloss

Domain decomposition methods for PDE constrained optimization

Location: Bürglsaal **Date:** Wednesday, July 5, 09:00 – 09:45

Domain Decomposition Methods (DDMs) are routinely used for the parallel solution of systems of partial differential equations (PDEs). More recently, they have been successfully applied to PDE constrained optimization problems. In the latter context, DDMs introduce parallelism at the optimization level, allow the design of preconditioners of so-called KKT systems arising within the optimization, but also offer opportunities for storage management and subdomain model reduction.

In this talk I will present DDMs for selected PDE constrained optimization model problems. While many of these DDMs are similar to DMMs that are well known for single PDEs, the optimization structure of the subdomain problems and their coupling used in the optimization level DDMs is quite different from the structure encountered in DMMs for PDEs. I will present numerical examples illustrating the performance of optimization level DDMs and I will discuss some theoretical results.

Hyea Hyun Kim

Domain decomposition algorithms for mortar discretizations

Location: Bürglsaal **Date:** Tuesday, July 4, 09:45 – 10:30

Mortar discretizations have been developed for coupling different approximations in different subdomains, that can arise from engineering applications in complicated structures with highly non-uniform materials.

The complexity of the discretizations requires fast algorithms for solving the resulting linear systems. We focus on extension of several domain decomposition algorithms, that have been successfully applied to conforming finite element discretizations, to solving such linear systems. They are overlapping Schwarz methods, FETI-DP (Dual-Primal Finite Element Tearing and Interconnecting) methods, and BDDC (Balancing Domain Decomposition by Constraints) methods.

The main contribution is that complete analysis, providing the optimal condition number estimate, has been done for geometrically non-conforming subdomain partitions and for problems with discontinuous coefficients. These algorithms are further extended to the two-dimensional Stokes and three-dimensional elasticity. In addition, an exact solver for the coarse problem has been developed, especially in the three dimensions.

Numerical computations present the performance of the suggested algorithms for the geometrically non-conforming partitions and for the problems with discontinuous coefficients. Performance of the algorithms equipped with an inexact coarse problem will also be presented.

This work has been carried out under collaborations with Professor Maksymilian Dryja, in Warsaw University, Poland, Professor Chang-Ock Lee, in KAIST, Korea, Professor Olof B. Widlund, and Doctor Xuemin Tu, at Courant Institute, USA.

Rolf Krause

On the multiscale solution of constrained problems in linear elasticity

Location: Bürglsaal **Date:** Friday, July 7, 09:45 – 10:30

In the talk, an abstract algorithmic framework for the solution of constrained convex minimization problems by monotone multigrid methods is presented, which is applicable to geometric as well as algebraic multigrid methods. Particular emphasis is put on the multiscale representation of the constraint set within a multilevel hierarchy, which is of crucial importance for the overall performance and convergence of multigrid based solution strategies for constraint problems. This is discussed in the context of frictional contact problems in elasticity. Although the method is based on the primal variables, i.e. the displacements, a close connection to the dual variables can be established by employing mortar methods for the discretization of the constraints and frictional nonlinearities at the contact interface. For the case of time dependent contact problems, we furthermore discuss, how undesirable oscillations at the contact boundary emerging from the time discretization can be significantly reduced by simply adding an additional projection at the interface. In combination with an implicit time discretization, this gives rise to an efficient and stable simulation method for time dependent contact problems in linear elasticity.

Finally, as an example for the flexibility of our approach, we consider the numerical solution of a multi-component phase-field model for elastically stressed solids.

Yuri Kuznetsov

Domain Decomposition Preconditioners for Anisotropic Diffusion

Location: Bürglsaal **Date:** Monday, July 3, 14:00 – 14:45

In this presentation, I will consider new nonoverlapping domain decomposition preconditioners for diffusion equations with anisotropic diffusion tensors. The model problems are relevant to applications in geosciences. Condition number estimates and numerical results will be given.

Raytcho Lazarov

Preconditioning of discontinuous Galerkin FEM of second order elliptic problems

Location: Bürglsaal **Date:** Tuesday, July 4, 14:00 – 14:45

The popularity of DG approximations in recent years is largely due to the nice features like local mass conservation and flexible choice of the finite element spaces. However, to make the method attractive for the computational practice it is necessary to develop fast and efficient solution methods for the corresponding system and means of reducing the excessive number of degrees of freedom. The latter could be achieved by hybridization, while the former could use preconditioning based on multigrid/multilevel and/or domain decomposition.

The talk summarises some recent results in preconditioning of algebraic systems arising in interior penalty DG approximations of second order elliptic problems. These were obtained jointly with my colleagues V. Dobrev, S. Margenov, P. Vassilevski, and L. Zikatanov.

We introduce the two-level iteration that uses the finite element space V of discontinuous functions and an auxiliary, in general smaller, space V_0. First we show the convergence of the two-level method for three particular choices of V_0, (1) continuous FE, (2) Crouzeix-Raviart nonconforming FE, (3) piece-wise constant functions, all defined on the original FE partition of the domain. The last space is quite interesting since it leads to a system with a "graph-Laplacian" matrix, which for general FE partitions does not have approximation property.

Further we investigate two possibilities for an algebraic multilevel extension of the two-level method in the case of piece-wise constant functions, one based on the algebraic multigrid method of Falgout, Vassilevski, and Zikatanov, NLAA, 2005, and the second that utilizes the algebraic multilevel iteration of Axelsson and Vassilevski, SINUM, 1990. Under certain assumptions we prove optimal convergence for both multilevel methods.

Young-Ju Lee

Convergence theories of the subspace correction methods for singular and nearly singular system of equations

Location: Bürglsaal **Date:** Thursday, July 6, 14:45 – 15:30

Many mathematical models lead to singular and/or nearly singular problems. Simple examples include the Laplace equation with the Neumann boundary condition, the nearly incompressible linear elasticity equations, variational problems in electromagnetism at certain parameter ranges (in general variational problems on H(div) and/or H(curl)). The main goal of this presentation is to report recent research results on the abstract convergence analysis for both singular and nearly singular system of equations. For singular problems, we will present a sharp convergence rate identity for general subspace correction methods. We then apply the abstract theory in the study of the convergence of the multigrid method for certain singular problems.

Our discussion of nearly singular problems will begin with a simple linear system and the difficulties that arise when solving such a system by a classical iterative method. To tackle these difficulties in the simple example, as well as in much more complicated situations, we introduce new abstract assumptions and based upon these assumptions we present a refined convergence analysis of a class of iterative methods via the subspace correction framework. Our new theory clearly shows the crucial role played by the right assumptions in obtaining optimal convergence rate estimates. As illustration, we present a convergence analysis of a multilevel method for the linear elasticity system discretized by high order conforming finite elements. In particular, our analysis shows that the proposed methods are uniformly convergent with respect to the mesh size, the number of mesh levels, and weights on the two terms in the inner product obtained by the relevant linear elasticity operator.

This report is based on the joint work with Jinbiao Wu, Jinchao Xu and Ludmil Zikatanov.

Günter Leugering

Domain decomposition in optimal control of partial differential equations on networked domains

Location: Bürglsaal **Date:** Wednesday, July 5, 09:45 – 10:30

We consider partial differential equations on networks, such as graphs or multiply linked domains. We focus on hyperbolic equations or systems of such equations and consider particularly final value optimal control problems. The point of the analysis is to decompose the corresponding optimality system in space and time such that the decomposed system is, in turn, an optimality system of a local optimal control problem in a more simple space-time domain, where standard optimal control software is applicable. Algorithms are presented on the infinite-dimensional level, well-posedness and convergence are discussed, and a posteriori error estimates with respect to the decomposition are provided. Recent applications are going to be presented.

Jacques Periaux

A domain decomposition / Nash equilibrium methodology for the solution of direct and inverse problems in fluid dynamics

Location: Bürglsaal **Date:** Tuesday, July 4, 14:45 – 15:30

The main goal of this lecture is to present the application of a decentralization optimization principle from Game Theory to the solution of direct and inverse problems in Fluid Dynamics. It will be shown in particular that multicriteria optimization methods "a la Nash" combine ideally with domain decomposition methods, with or without overlapping in order to solve complex problems. The resulting methodology is flexible and in the case of design problems has shown to perform well when using adjoint based techniques or evolutionary algorithms for the optimization.

The above methodology will be applied to the simulation and shape and position optimization for flows in nozzles and around aerodynamical shapes.The results of various numerical experiments will show the efficiency of the methods presented here.

Olaf Steinbach

Boundary element domain decomposition methods: challenges and applications

Location: Bürglsaal **Date:** Thursday, July 6, 09:45 – 10:30

Domain decomposition methods are usually based on the solution of local boundary value problems to perform the corresponding Dirichlet to Neumann maps. When using boundary integral equations the associated Steklov-Poincare operators can be defined via boundary potentials only. The discretisation afterwards can be realised by fast boundary element methods such as the fast multipole approach or by using hierarchical matrices. In this talk we give an overview on different formulations of boundary element domain decomposition methods and we will discuss the efficiency of the resulting algorithms and we will include several applications.

Mary Wheeler

A domain decomposition multiscale mortar mixed method for flow in porous media

Location: Bürglsaal **Date:** Friday, July 7, 09:00 – 09:45

A fundamental difficulty in understanding and predicting large-scale fluid movements in porous media is that these movements depend upon phenomena occuring on small scales in space and/or time. The differences in scale can be staggering. Aquifers and reservoirs extend for thousands of meters, while their transport properties can vary across centimeters, reflecting the depositional and diagenetic processes that formed the rocks. In turn, transport properties depend on the distribution, correlation and connectivity of micron sized geometric features such as pore throats, and on molecular chemical reactions. Seepage and even pumped velocities can be extremely small compared to the rates of phase changes and chemical reactions.

We will focus on the mortar mixed finite element method (MMFE) which was first introduced by Arbogast, Cowsar, Wheeler, and Yotov for single phase flow and later extended to multiphase flow by Lu, Pesyznska, Wheeler, and Yotov. The MMFE method is quite general in that it allows for non-matching interfaces and the coupling of different physical processes in a single simulation. This is achieved by decomposing the physical domain into a series of ubdomains (blocks) and using independently constructed numerical grids and possibly different discretization techniques in each block. Physically meaningful matching conditions are imposed on block interfaces in a numerically stable and accurate way using mortar finite element spaces. This domain decomposition approach can be viewed as a subgrid or two scale approach. Moreover, the use of mortars allows one to couple MFE and discontinuous Galerkin approximations in adjacent subdomains. In this presentation we will discuss theoretical a priori and a posteriori results and computational results will be presented.

Part III

Abstracts of Minisymposium Talks

M01

Advanced multigrid methods for systems of PDEs
Organized by Panayot Vassilevski and Ludmil Zikatanov

The main theme of the minisymposium is on the advanced multigrid techniques and their applications. The focus is on the solution of large scale linear systems that typically come from discretizations of systems of PDEs. Examples of such applications are found in numerical models used in electromagnetics, flow simulation, and elasticity.

Jay Gopalakrishnan, Joseph Pasciak

Multigrid convergence for axisymmetric problems

Location: S2 **Date:** Monday, July 3, 17:30 – 17:55

We present a convergence analysis of the geometric V-cycle algorithm for axisymmetric Laplace and Maxwell equations. The interest in these problems is due to the dimensional reduction made possible by axial symmetry. However the reduced problems have degenerate coefficients. Although multigrid convergence is hampered in many problems with degenerate coeffcients, we show that for the reduced axisymmetric problems, the standard V-cycle with point smoothing converges at a rate independent of the number of unknowns. We prove this for a simple model problem by developing a few new results on finite element convergence and regularity of axisymmetric Maxwell equations.

Johannes Kraus

On the construction of a hierarchical topology with application to algebraic multilevel preconditioning

Location: S2 **Date:** Tuesday, July 4, 17:00 – 17:25

We focus on generating hierarchies of topological relations for unstructured three-dimensional (3D) finite element (FE) meshes. The related topological elements are agglomerated elements (volumes), faces, edges (and vertices). In this context we provide practical definitions and propose efficient procedures for the setup of coarse faces and coarse edges. Moreover, we examine the agglomeration algorithm introduced by Jones and Vassilevski [1] and suggest a proper generalization to 3D problems [2].

This setting allows for a recursive construction of nested sequences of topological elements that can be exploited in different areas of finite element computations, e.g., domain decomposition, or algebraic multigrid methods.

Here we address the utilization of the hierarchical topology in the framework of algebraic multilevel preconditioning, which is based on a particular (hierarchical) basis transformation in this case. Consequently, existing multilevel methods of additive and multiplicative type can be applied to 3D-FE problems even if the underlying (finest) mesh is completely unstructured.

[1] J. Jones and P. Vassilevski, *AMGe based on element agglomeration*, SIAM J. Sci. Comput. 23 (2001), 109-133.
[2] J. Kraus and J. Synka, *An agglomeration-based multilevel topology concept with application to 3D-FE meshes*, RICAM-Report No. 2004-08, Linz, Austria

Svetozar Margenov, Raytcho Lazarov

CBS constants for graph-Laplacians and application to multilevel methods for discontinuous Galerkin systems

Location: S2 **Date:** Tuesday, July 4, 16:00 – 16:25

The goal of this work is to derive and justify a multilevel preconditioner for symmetric discontinuous approximations of second order elliptic problems. Our approach is based on the following simple idea. The finite element space of piece-wise polynomials of certain degree that are discontinuous on the certain partition is projected onto the space of piece-wise constants on the same partition. This will constitute the finest space in the multilevel method. The projection of the discontinuous Galerkin system on this space is associated to the so-called "graph-Laplacian". In 2-D this is a very simple M-matrix with -1 as off diagonal entries and current diagonal entries equal to the number of the neighbours through the interfaces of the current finite element. Then after consecutive aggregation of the finite elements we produce a sequence of spaces of piece-wise constant functions. We develop the concept of hierarchical splitting of the unknowns and using local analysis we derive uniform estimates for the constant in the strengthen Cauchy-Bunyakowski-Schwarz (CBS) inequality. As a measure of the angle between the spaces of the splitting, this further is used to justify a multilevel preconditioner of the discontinuous Galerkin system in spirit of the AMLI methods introduced in the pioneering work of Axelsson and Vassilevski.

Yvan Notay

Two-grid convergence implies unconditionally W-cycle convergence

Location: S2 **Date:** Monday, July 3, 17:00 – 17:25

We consider multigrid methods for symmetric positive definite linear systems. We present a new algebraic convergence analysis of two-grid schemes with inexact solution of the coarse grid system. This analysis allows us to bound the convergence factor of such perturbed two-grid schemes, assuming only a certain bound on the convergence factor for the unperturbed scheme (with exact solution of the coarse grid system). Applied to multigrid methods with standard W–cycle, this analysis shows that if the convergence factor of the (unperturbed) two-grid method is uniformly bounded by $\sigma < 1/2$, then the convergence factor of the multigrid method is uniformly bounded by $\sigma/(1-\sigma)$. The analysis is purely algebraic and requires only that pre- and post-smoothing are applied in a symmetric way. It covers both geometric and algebraic multigrid methods, and the coarse grid matrix may be of any type (not necessarily Galerkin).

François Musy, Laurent Nicolas, Ronan Perrussel, Michelle Schatzman

Algebraic multigrid strategies based on De Rham complexes on graphs with applications to Maxwell's equations

Location: S2 **Date:** Monday, July 3, 16:30 – 16:55

For solving linear systems coming from edge element discretization with algebraic multigrid strategies, the importance of a gradient-prolongation commutativity has been shown in [1]. This specificity and is also exploited in [2, 3]. Underlying these approaches is the construction of a coarse topology or at least a coarse edge – coarse node incidence graph. We have formulated a property that the constructed coarse graph has to satisfy in order to enforce the gradient-prolongation commutativity: this condition is expressed in terms of connectivity of subgraphs of the coarse graph [4].

Based on a coarse graph satisfying this property and a given nodal prolongator, graph algorithms can be used to determine a compatible edge prolongator and to identify the parameters which can be adjusted. These remaining parameters can be computed by minimizing some energy functionals. Numerical examples will be presented to evaluate the effectiveness of the edge prolongator obtained with this approach.

[1] S. Reitzinger and J. Schöberl, *An algebraic multigrid method for finite element discretizations with edge elements*, Numer. Linear Algebra Appl., 9:223–238, 2002

[2] J. J. Hu et al., *Toward an h-independent algebraic multigrid method for Maxwell's equations*, SIAM J. Sci. Comput., 27(5):1669–1688, 2006

[3] T. Boonen, G. Deliége and S. Vandewalle, *On algebraic multigrid methods derived from partition of unity nodal prolongators*, Numer. Linear Algebra Appl., 13(2-3):105–131, 2006

[4] F. Musy, L. Nicolas and R. Perrussel, *Gradient-prolongation commutativity and graph theory*, C. R. Acad. Sci. Paris, 341(11):707–712, 2005

Joachim Schöberl

Robust preconditioning in elasticity

Location: S2 **Date:** Monday, July 3, 16:00 – 16:25

This presentation is a continuation on earlier work on robust multigrid components for nearly incompressible elasticity. The smoother is a block-smoother capturing a local decomposition of the discrete divergence-free sub-space. The grid-transfer operators map divergence-free sub-spaces form one to the other level. The method is applied to elements resulting from the hybridization of a new mixed formulation. These elements have a minimal number of degrees of freedom.

Johannes Kraus, Satyendra Tomar

Multilevel preconditioning of elliptic problems discretized by a class of discontinuous Galerkin methods

Location: S2 **Date:** Tuesday, July 4, 16:30 – 16:55

Optimal order preconditioners obtained from recursive application of two-level finite element (FE) methods have been introduced and extensively analyzed in the context of conforming methods [1,2]. More recently, some extensions related to Crouzeix-Raviart or Rannacher-Turek non-conforming finite elements have also been considered [3]. For this kind of discretization schemes the finite element spaces corresponding to two successive levels of mesh refinement are not nested in general.

In this paper we address a different class of nonconforming methods, i.e., arising from certain discontinuous Galerkin (DG) finite element discretizations. We consider here the interior penalty (IP) DG method and other formulations with a similar stabilization term. In this case the hierarchy of meshes is geometrically nested. We propose a specific assembling process which fits the general framework of constructing two-level preconditioners for conforming methods. This allows for a local definition of different variants of hierarchical splittings and also to study the angle between the resulting subspaces. Thus, our approach can be viewed as a straightforward extension of the conforming case. In particular, we avoid a decomposition of the FE space associated with the DG approximation into a (coarser) auxiliary space (for which there exist multilevel or other efficient solution techniques) plus a correction, see [4]. Instead, we generate a sequence of algebraic problems that can be associated with a hierarchy of coarse versions of DG approximations of the original problem.

We derive new bounds for the constant γ in the strengthened Cauchy - Bunyakowski - Schwarz inequality which measures the quality of the underlying splitting. In the limiting case of the penalty parameter (e.g., in the IP method) approaching infinity, the bounds correspond to those for conforming (bilinear) elements. The presented numerical results demonstrate the potential of this approach.

[1] O. Axelsson and I. Gustafsson, *Preconditioning and two-level multigrid methods of arbitrary degree of approximations*, Math. Comp., 40(1983), 219-242

[2] O. Axelsson and P. S. Vassilevski, *Algebraic multilevel preconditioning methods I*, Numer. Math., 56 (1989), 157-177

[3] R. Blaheta, S. Margenov, M. Neytcheva, *Robust optimal multilevel preconditioners for non-conforming finite element systems*, Numerical Linear Algebra with Applications, 12 (2005), 495-514

[4] R. Lazarov, P. Vassilevski, L. Zikatanov, *Multilevel preconditioning of second order elliptic discontinuous Galerkin problems*, Preprint, 2005

Tzanio V. Kolev, Panayot Vassilevski

Agglomeration AMGe with local constrained energy minimization interpolation

Location: S2 **Date:** Monday, July 3, 18:00 – 18:25

We will present an AMG (algebraic multigrid) method that utilizes energy minimization construction of the interpolation matrices locally, in the setting of element agglomeration AMG. The coarsening in element agglomeration AMG is done by agglomerating fine-grid elements, with coarse element matrices defined by a local Galerkin procedure applied to the matrix assembled from the individual fine-grid element matrices. This local Galerkin procedure involves only the coarse basis restricted to the agglomerated element. To construct the coarse basis, one exploits previously proposed constraint energy minimization procedures now applied to the local matrix. The constraints are that a given set of vectors should be interpolated exactly, not only globally, but also locally on every agglomerated element. The talk will provide algorithmic details, as well as a convergence result based on a “local-to-global” energy bound of the resulting multiple-vector fitting AMG interpolation mappings. A particular implementation of the method is illustrated with a set of numerical experiments.

This is a joint work with Tzanio V. Kolev (CASC, LLNL).

This work was performed under the auspices of the U. S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

Durkbin Cho, Ludmil Zikatanov

Uniform preconditioning of a generalized finite element method discretizations

Location: S2 **Date:** Tuesday, July 4, 17:30 – 17:55

We consider the symmetric positive semi-definite problems arising from generalized finite element discretizations on unstructured grids. The focus will be on an auxiliary space method, in which the auxiliary space is spanned by the partition of unity functions. We characterize the kernel components of the stiffness matrix for some GFEM discretizations in two and three spatial dimensions. We prove a uniform bound on the condition number of the preconditioned system in an appropriate quotient space.

M02

DD based on boundary elements
Organized by Olaf Steinbach and Wolfgang Wendland

As it is well known, for non-overlapping domain decomposition methods the Steklov-Poincare operator or its inverse play a dicisive role. We therefore propose a minisymposium on the above topic. In corresponding research during the last decades remarkable achievements have been made.

Jiri Bouchala, Zdenek Dostal, Marie Sadowska

Scalable BETI based algorithms for numerical solution of variational inequalities

Location: S2 **Date:** Thursday, July 6, 17:00 – 17:25

We shall first briefly review the BETI based domain decomposition methodology adapted to the solution of variational inequalities such as those describing the equilibrium of a system of bodies in mutual contact. As a result, we shall obtain a convex quadratic programming problem with bounds and equality constraints. Using the classical results concerning the solution of linear elliptic boundary value problems, we shall show that the spectrum of the Hessian matrix of the quadratic form is independent on the discretization parameter h.

Then we shall present the algorithms for the solution of resulting quadratic programming problems. The unique feature of these algorithms is their capability to solve the class of quadratic programming problems with the spectrum in a given positive interval in $\mathcal{O}(1)$ iterations. Finally we put together results on the approximation of variational inequalities and those on quadratic programming to get scalable algorithms for the solution of both coercive and semicoercive variational inequalities. We give the results of numerical solution of a model problem to illustrate our results numerically.

Ralf Hiptmair

Resonance free interface coupled BEM for Maxwell's equations

Location: S2 **Date:** Thursday, July 6, 16:00 – 16:25

Domain decomposition ideas bulk large in the field of computational electromagnetism, where one often encounters different crisply defined physical bodies with complex shapes interacting with electromagnetic fields. In many cases their material properties are simple, that is, they are linear and homogeneous. This is just the right environment for boundary element methods.

Formally, the coupling between sub-domain relies on transmission conditions and local Poincaré-Steklov operators expressed through Calderon projectors. A similar technique also forms the foundation for the symmetric coupling of finite elements and boundary elements. However, for Maxwell's equations in the frequency domain this leads to variational problems with a well-known instability at certain resonant frequencies. Surprisingly, the same coupling idea applied to boundary integral equations alone, does not suffer from such an instability.

Good stability properties translate into quasi-optimality of Galerkin solutions. This can be shown appealing to coercivity of the variational problem with respect to a Hodge-type decomposition of the electromagnetic trace spaces.

W.Hackbusch, B.N.Khoromskij, Alexander Litvinenko

$\mathcal{H}$-matrix based preconditioner for the skin problem

Location: S2 **Date:** Thursday, July 6, 18:00 – 18:25

In this talk we discuss an interface based preconditioner to the so-called skin problem. For the skin problem it is typical to have highly jumping coefficients (the penetration coefficient inside of cells is very low $\sim 10^{-5} - 10^{-3}$, but it is large between cells ~ 1). The corresponding equation has the form:

$$\begin{aligned} \operatorname{div}(\alpha(x,y)\nabla u) = 0 \qquad & \text{in } \Omega, \\ u = g \qquad & \text{on } \partial\Omega, \end{aligned}$$

where $\alpha \ll 1$ in cells and $\alpha = 1$ in between. The thin layer between cells defines the decomposition of Ω. The width of the layer between cells is $const \cdot h$ (i.e., proportional to the discretisation step). For the solution of this problem we apply the preconditioned CG method. The matrix

$$\begin{pmatrix} A_{II}^{-1} & 0 \\ 0 & diag(A_{DD})^{-1} \end{pmatrix},$$

where A_{II} is the interface-interface matrix and A_{DD} is the domain-domain matrix, is used as a preconditioner. We apply the $\mathcal{H}$-matrix technique [1] for computing the approximation of A_{II}^{-1}. The complexity of the $\mathcal{H}$-matrix inverse is $\mathcal{O}(n_I \log^2 n_I)$, where n_I is the number of degrees of freedom in the interface layer. In conclusion we compare our preconditioner with $\mathcal{H}$-LU preconditioner. Since our method does not require approximation of A_{DD}^{-1} the computational resources are smaller.

[1] W. Hackbusch, *A sparse matrix arithmetic based on $\mathcal{H}$-matrices. Part 1: Introduction to $\mathcal{H}$-matrices*, Computing, 62: 89-108, 1999

[2] W. Hackbusch, *Direct Domain Decomposition using the Hierarchical Matrix Technique*, pp. 39-50, Domain Decomposition Methods in Sci. and Engineering. Cocoyoc, Mexico, 2003

[3] W. Hackbusch, B. N. Khoromskij and R. Kriemann, *Direct Schur Complement Method by Hierarchical Matrix Techniques*, Computing and Visualisation in Science, 2005, 8: 179-188

[4] B. N. Khoromskij and G. Wittum, *Numerical Solution of Elliptic Differential Equations by Reduction to the Interface*, LNCSE 36, Springer, 2004

Clemens Pechstein, Ulrich Langer

Coupled FETI/BETI solvers for nonlinear potential problems in unbounded regions
Location: S2 **Date:** Thursday, July 6, 16:30 – 16:55

This contribution deals with the numerical solution of nonlinear potential equations of the form

$$-\nabla \cdot [\nu(x, |\nabla u(x)|) \nabla u(x)] = f(x),$$

for $x \in \mathbf{R}^d = \overline{\Omega} \cup \overline{\Omega}^c$, arising e. g. in 2D magnetic field computations ($d = 2$). On the exterior space Ω^c we assume that $f \equiv 0$ and $\nu \equiv \nu_0 =$ const, and that the radiation condition $|u(x)| = \mathcal{O}(|x|^{-1})$ holds for $|x| \to \infty$. We apply Newton's method to the nonlinear variational formulation and solve the linearized problems with coupled Finite and Boundary Element Tearing and Interconnecting (FETI/BETI) methods.

In case of a nonlinear coefficient, the spectrum of the corresponding subdomain Jacobi matrix may show high variation, which is the typical behavior of the reluctivity on ferromagnetic subdomains. We propose a special preconditioner in order to overcome these problems.

The condition number of the preconditioned FETI/BETI system corresponding to a boundary value problem on Ω can be estimated by $C(1 + \log(\frac{H}{h}))2$. Here, C is a constant independent of the mesh size h, the maximal subdomain diameter H and jumps in the coefficients accross subdomain interfaces. Including the exterior space as a subdomain, a weak dependence of the number of subdomains touching the exterior space can be observed in the numerical experiments.

In order to get a good initial guess for the Newton iteration, we use the nested iteration strategy based on a hierarchy of nested grids. Finally, we discuss our first numerical results obtained from the numerical solution of some 2D magnetostatic model problems.

Dehao Yu

The natural boundary reduction and the domain decomposition methods in unbounded domains
Location: S2 **Date:** Thursday, July 6, 17:30 – 17:55

The natural boundary integral operator, which is also known as the Steklov-Poincare operator or Dirichlet to Neumann (DtN) map, plays a very important role in domain decomposition methods. In this talk some new development of the natural boundary integral method and related domain decomposition methods for solving problems in unbounded domains are presented. These methods are efficient for many kinds of exterior problems. Some numerical examples are given to illustrate the effectiveness of these methods.

M03

DD in coupled engineering phenomena with multiple scales
Organized by Richard Ewing, Oleg Iliev and Raytcho Lazarov

The intent of the minisymposium is to discuss the state of the art and the perspectives in approximation and solution strategies related to Domain Decomposition methods for coupled phenomena in physics and engineering that involve multiple models and/or multiple space and time scales. All invited speakers are experts in domain decomposition, numerical methods for coupling various complex physical phenomena, multi-scale methods, and engineering application.

Heiko Andrä, Andreas Wiegmann, Aivars Zemitis

Application of domain decomposition methods in micromechanics
Location: B1 **Date:** Thursday, July 6, 16:00 – 16:25

Many industrial and engineering materials as well as most "natural" materials are inhomogeneous, i.e., they consist of dissimilar components or phases. One important aim of micromechanics for inhomogeneous materials lies in homogenization, i.e., in computing the effective thermo-elastic behavior from the material behavior of the components and of the interface between them.

We consider materials (e.g. open cell foams, granular materials) which possess complex microstructures which result in large representative volume elements (RVE). The voxel approximations of such RVEs are obtained from three-dimensional CT images ("real structure" RVE) or by statistical reconstruction in the computer.

For the fast computation of the effective material parameters, two domain decomposition approaches are proposed. The first approach is developed for the estimation of the effective thermal conductivity especially of composite materials. The necessary solution of the elliptic b.v.p. is obtained in two steps. During the first step, only jumps of the first derivatives on the boundaries between the two different materials are calculated. The corresponding linear system for the considered materials is much smaller than the original one and, therefore, a Schur complement method can be used efficiently. In the next step the solution in the whole domain is obtained by using FFT. The second method is a variant of FETI for the computation of the effective elastic stiffness tensor.

In the proposed approach, fully automated mesh generation is combined with fast solution methods. This allows to accelerate the whole procedure of virtual design of microstructures and computing macroscopic material parameters. Therefore, the methods are most appropriate for virtual material design and material optimizations.

Numerical tests for foams and fibrous materials are presented, where the voxel discretization of the RVE is compared to standard finite element meshes for the RVE.

Paola F. Antonietti, Blanca Ayuso

Class of preconditioners for discontinuous Galerkin approximations of elliptic problems
Location: B1 **Date:** Thursday, July 6, 16:30 – 16:55

In this talk, we introduce a unified framework for the construction of Schwarz preconditioners for all the discontinuous Galerkin (DG) approximations of elliptic problems that have been proposed up to the date. We shall introduce two level additive and multiplicative iterative methods for both symmetric and non-symmetric DG schemes, and we will discuss some new interesting features arising from the analyses, which have no analogue in the conforming case. Optimal rates of convergence will be established for the resulting iterative methods. We will present extensive numerical experiments to assess and support the theoretical results and to further illustrate the performance and robustness of the proposed methods. Finally, a comparison between the additive and multiplicative preconditioners will be shown to illuminate the pros & cons of both methods.

Petter Bjørstad, Jan M. Nordbotten

On the relationship between domain decomposition preconditioners and the multiscale finite volume method
Location: B1 **Date:** Tuesday, July 4, 17:00 – 17:25

A domain decomposition preconditioner for solving the elliptic potenital equation in reservoir flow modeling is presented. The method satisfies mass conservation on the dual coarse grid exactly, which allows for postprocessing.

Jorg Aarnes, Yalchin Efendiev

An adaptive multiscale method for simulation of fluid flow in heterogeneous porous media
Location: B1 **Date:** Tuesday, July 4, 16:30 – 16:55

In this talk, I will present multiscale simulation techniques for porous media flows. Multiscale finite element methods and their applications to porous media flows in heterogeneous media will be discussed. An adaptive multiscale technique for hyperbolic equations and the use of limited global information in multiscale finite element methods will be presented.

Richard Ewing, Guan Qin

Domain decomposition techniques for treating multiscale properties in reservoir engineering applications
Location: B1 **Date:** Tuesday, July 4, 16:00 – 16:25

The ability to numerically simulate multiphase flows of fluids in underground reservoirs is a major tool in the optimization of production of hydrocarbons in petroleum engineering applications. The flow is complicated by the presence of heterogeneities in the reservoir at many different length scales. These multi-scale effects must be effectively modeled by terms in complex multiphase reservoir simulators. The flows in certain parts of the reservoir might be very stable and simple, while the velocities in other parts might vary strongly in both space and time due to spatial heterogeneities of phase changes in the fluids. Many types of upscaling and downscaling have been applied to reservoir simulation. When the flow is so complex that an upscaled model will not resolve the physics of the flow, adaptive local grid refinement and associated local time-stepping techniques are necessary. We will present patch approximation techniques that lead to block systems that can be solved very effectively with domain decomposition techniques. These techniques, coupled with upscaling techniques for simpler flows or simpler physics can be utilized to effectively concentrate the computing power where it is needed.

Jay Gopalakrishnan

A hybridization approach to coupling methods
Location: B1 **Date:** Thursday, July 6, 17:00 – 17:25

We present a unified framework for hybridizing a variety of Galerkin methods. This framework allows hybridization of certain types of discontinuous Galerkin (DG) methods, resulting in DG formulations competitive with mixed methods in number of unknowns, thus eliminating the criticism that DG methods have too many unknowns. The unified framework also facilitates discovery of new methods and comparison between methods. This talk will highlight the ease of generation of mortaring techniques within this framework, allowing one to couple different methods, even across non-matching mesh interfaces.

Oleg Iliev, Raytcho Lazarov, Joerg Willems

On a two-level domain decomposition preconditioner for 3D Stokes flow in highly complicated geometry
Location: B1 **Date:** Tuesday, July 4, 18:00 – 18:25

Stokes system of equation is considered to describe flow of incompressible fluid at pore scale. Two-level DD preconditioner is developed for solving the above problem. At the fine scale, a projection type method for Stokes problem is used as a smoother. An important part of the algorithm is the selection of the coarse scale operator. Coarse scale problem described by Brinkman system of equations is described here. The coefficients of the coarse scale equation are obtained via homogenization of the fine scale Stokes problem. Results from numerical experiments are presented and discussed.

R.E. Ewing, O.P. Iliev, R.D. Lazarov, Iryna Rybak

On a two-level domain decomposition preconditioner for 3D flows in anisotropic highly heterogeneous porous media
Location: B1 **Date:** Tuesday, July 4, 17:30 – 17:55

The talk concerns a two level DD type preconditioner for 3D elliptic equation with highly varying discontinuous tensor coefficients. Discretization is based on finite volume approach and multipoint flux approximation approach. The domain is divided into subdomains in the style of DD. Additive Schwarz method is implemented as a smoother within a two level preconditioner. The choice of the intergrid (interlevel) operators, as well as the choice of the coarse scale operator, are critical for the convergence of the method. Solutions of the local problems (i.e., in each subdoman) are postprocessed in order to upscale the permeability tensor, in this way the coarse scale operator is obtained from a homogenization type procedure. Obviously, the interface conditions for the DD method influence the coarse scale operator in particular, and the convergence of the overall iterative method in general. The influence of the overlapping is studied, as well the influence of the choice of the boundary (interface) conditions between subdomains. It is known, that in the case of periodic media the obtained in this way coarse scale equation can be considered as effective (upscaled) equation for the media. Thus, for the given periodic porous media, it is enough to solve once at the fine scale, all further problems for the same geometry can be solved using the upscaled equation. Applicability of the obtained coarse scale equation for the case of non-periodic porous media is also studied.

M04

DD methods motivated by the physics of the underlying problem

Organized by Martin Gander and Laurence Halpern

Domain decomposition methods are a powerful tool to handle very large systems of equations. They can however also be used to couple different physical models or approximations, which one might want to do for various reasons: in fluid structure coupling for example, the physical laws in the fluid differ from the physical laws in the structure, and a domain decomposition method could naturally take this into account. Even if the physical model is the same, one might want to use a simplified equation in part of the domain, where certain effects are negligible, like for example in aerodynamics, to save computation time. Or one could simply want to use a much coarser mesh, like in combustion away from the flame front, which again could be taken naturally into account by a domain decomposition method that can handle non-matching grids, possibly in space and time.

The speakers in this minisymposium present recent research results covering the wide aspects of domain decomposition methods motivated by the physics of the underlying problem. Topics include Schwarz waveform relaxation methods with moving meshes, optimized transmission conditions and non-matching grids, coupling of advection and advection diffusion problems, optimized transmission conditions for the Schroedinger equation and domain decomposition methods in micro-magnetics.

Ronald Haynes, Bob Russell

Towards a Schwarz waveform moving mesh solver

Location: B2 **Date:** Tuesday, July 4, 16:30 – 16:55

It is now well accepted that efficient and robust methods to solve challenging problems in scientific computing require strategies which adapt to evolving features of the solution. To solve mathematical problems in the guise of partial differential equations this necessitates methods which provide adaptivity in both space and time. In this talk I will provide a brief review of r-refinement methods (ie. moving mesh methods). The implementation of a moving mesh requires the solutions of a coupled system of PDEs: the physical PDEs as well as a PDE which dictates mesh movement. To take advantage of local time scales in the solution this system of PDEs has been solved in a Schwarz Waveform framework culminating in a new Schwarz Waveform Moving Mesh Method. Preliminary results will be reviewed along with an update on recent work on new 2D and 3D solvers.

Caroline Japhet

Coupling of heterogeneous advection - diffusion problems with an optimized Schwarz waveform relaxation method and nonconforming time discretisation

Location: B2 **Date:** Tuesday, July 4, 16:00 – 16:25

We present and study an optimized Schwarz Waveform Relaxation algorithm for convection - diffusion problems with discontinuous coefficients. Such methods have proven to be an efficient approach in the case of the wave equation with discontinuous wave speed (see [4]), and convection - difusion problems in 1d [3] or 2d [5]. Our final objective is to propose efficient algorithms for coupling heterogeneous models (e.g. ocean - atmosphere) in the context of climate modelling. The SWR algorithms are global in time, and thus allow for the use of non conforming space - time discretizations. They are therefore well adapted to coupling models with very different spatial and time scales, as in ocean - atmosphere coupling. As the cost per iteration can be very high, we introduce optimized transmission conditions in the algorithm. In order to get higher order schemes in time, we use in each subdomain a discontinuous Galerkin method (see [2]) for the time - discretization. This approach has been introduced in [1], with promising numerical results in the case of a discontinuous Galerkin method based on $\mathbb{P}_0$ approximations. We propose to extend this approach to $\mathbb{P}_1$ finite element approximations.

[1] E. Blayo, L. Halpern, C. Japhet, *Optimized Schwarz Waveform Relaxation algorithms with nonconforming time discretization for coupling convection - diffusion problems with discontinuous coefficients*, Proceedings of the Sixteenth International Conference on Domain Decomposition Methods, New-York, ddm.org, 2005

[2] C. Johnson, *Numerical solution of partial differential equations by the finite element method* , New York: Cambridge University Press, 1987

[3] D. Bennequin, M. J. Gander, L. Halpern, *Optimized Schwarz Waveform Relaxation for Convection Reaction Diffusion Problems*, submitted

[4] M. J. Gander, L. Halpern, F. Nataf, *Optimal Schwarz Waveform Relaxation for the one dimensional Wave Equation*, SIAM Journal on Numerical Analysis, Vol. 41, No 5, pp. 1643-1681, 2003

[5] V. Martin, *An optimized Schwarz waveform relaxation method for the unsteady convection diffusion equation in two dimensions*, Appl. Numer. Math. 52 (2005), No 4, 401–428

François-Xavier Roux

Approximate optimal interface conditions for fluid structure coupling in vibro-acoustics
Location: B2 **Date:** Tuesday, July 4, 17:30 – 17:55

The noise in a car or a plane cabin involves interaction between vibration of structure and sound propagation in air. In the frequency domain, this fluid-structure coupling is modelled by the coupling between the Helmholtz equation for the pressure in the fluid and the harmonic Lam equation for the displacement of the structure. The coupling terms link the normal derivative of the pressure with the velocity of the structure and the normal force applied by the fluid on the structure with the pressure. The matrix of the discrete coupled problem is very ill conditioned, due to the mixed character of the system. Furthermore, the method of choice for the numerical simulation of this vibro-acoustic problem consists in coupling existing structural analysis and acoustic codes instead of integrating both fluid and structure equations in a single complex new one. Hence, only iterative methods can be considered for solving the coupled system of equations. The iterative method can be naturally preconditioned by solving the sub-systems associated with either the fluid or the structural domain, like in domain decomposition methods. In this paper we compare two general methodologies for solving this kind of coupled problems. The first one consists in building a preconditioner for the global coupled system of equations using the exact solution of local problems in the fluid and the structural domains. Such a preconditioner can be interpreted as an approximate factorization technique. The second one consists in using the FETI-H domain decomposition method between two subdomains, one of them containing either the fluid or the structure plus the interface. In both cases, absorbing boundary conditions along the interface based on the computation of local approximation of the Schur complement of the outer domain are implemented in order to speed up the convergence of the methods.

Kévin Santugini

Challenges of applying domain decompostion methods to micromagnetism
Location: B2 **Date:** Tuesday, July 4, 17:00 – 17:25

Applying domain decompositions methods to micromagnetism presents some interesting challenges. First, the governing Landau-Lifshitz equation is a strongly nonlinear PDE. Second, weak solutions are not unique, therefore it is conceptually possible that a domain decomposition method converges to a solution which is different from the solution that would have been computed without domain decomposition. Finally, the magnetostatic term in micromagnetism is completely global, and the current methods to compute it efficiently are not easily compatible with domain decomposition. We will present numerical results on the convergence of different domain decomposition methods in micromagnetism.

Laurence Halpern, <u>Jeremie Szeftel</u>

Optimized and quasi-optimal Schwarz waveform relaxation for the one dimensional Schrödinger equation
Location: B2 **Date:** Tuesday, July 4, 18:00 – 18:25

We design and study Schwarz Waveform relaxation algorithms for the linear Schroedinger equation with a potential in one dimension. We show that the overlapping algorithm with Dirichlet exchanges of informations on the boundary is slowly convergent, and we introduce two new classes of algorithms: the optimized Robin algorithm and the quasi-optimal algorithm. We study the well-posedness and convergence, in the overlapping and the non overlapping case, for constant or non constant potentials. We then design a discrete algorithm, based on a finite volumes approach, which permits to obtain convergence results through discrete energies. We also present a quasi-optimal discrete algorithm, based on the transparent discrete boundary condition of Arnold and Ehrhardt. Numerical results illustrate the performances of the methods.

M05

FETI, balancing, and related hybrid DD methods
Organized by Barbara Wohlmuth, Olof Widlund and Axel Klawonn

Finite Element Tearing and Interconnecting (FETI) and Balancing Domain Decomposition methods are two related families of iterative substructuring algorithms which are by now quite well-known. In this minsymposium we would like to gather several active researchers in the field who are going to present their latest results. The topics of the tentative titles include different applications, e.g., elasticity, contact, acoustics, vibro-acoustics, and different discretizations, e.g., boundary elements, spectral elements, finite elements, discontinuous Galerkin.

Susanne Brenner, Li-yeng Sung

BDDC and FETI-DP without matrices or vectors
Location: S1 **Date:** Monday, July 3, 16:00 – 16:25

In this talk we discuss the connection between the BDDC algorithm and the FETI-DP algorithm in an abstract framework that uses the language of function spaces, operators and linear functionals.

Duilio Conceicao, Marcus Sarkis

BDD and BDDC preconditioners for stabilized GLS Oseen equations
Location: S1 **Date:** Tuesday, July 4, 17:00 – 17:25

In this talk we first present extensions of the BDD and BDDC preconditioners for stabilized (GLS) advection-diffusion equation in advective dominated regimes. This equation leads to a non-symmetric positive definide linear system where the skew-symmetric part of the system is large compared to the symmetric part. Several local and global problems are discussed. We then develop BDD and BDDC for the Stokes systems with enriched coarse spaces suitable for unstructured meshes that satisfy the inf-sup condition making the preconditioner scalable. A new enriched mixed finite element space will be introduced whose computational cost is of the same order of the low order discretization, however with high precision. We finaly extend these techniques for the stabilized Oseen equations.

Clark Dohrmann, Axel Klawonn, Olof Widlund

Algebraic coarse spaces for overlapping Schwarz preconditioners
Location: S1 **Date:** Thursday, July 6, 16:00 – 16:25

An algebraic approach is presented to construct coarse spaces for overlapping Schwarz preconditioners. The approach uses energy minimizing extensions of coarse trace spaces, and can be viewed as a generalization of earlier work by Dryja, Smith, and Widlund. Compared with BDDC and FETI-DP, the approach does not require access to individual subdomain matrices. Rather, it works directly with the assembled problem matrix. In addition, coarse spaces for more difficult problems like nearly incompressible elasticity can be constructed more easily.

Using the coarse space in an overlapping Schwarz preconditioner leads to condition numbers bounded by $C(1 + H/\delta)(1 + \log(H/h))$ for certain problems when coefficient jumps are aligned with subdomain boundaries. For problems without coefficient jumps, it is possible to remove the $\log(H/h)$ factor in the bound by a suitable enrichment of the coarse space. Numerical examples are presented for the Poisson equation, compressible and nearly incompressible elasticity, and plate bending.

Zdenek Dostal, David Horak, Dan Stefanica, Oldrich Vlach

Scalable FETI/FETI-DP based algorithms for numerical solution of variational inequalities with dissipative term
Location: S1 **Date:** Monday, July 3, 17:30 – 17:55

We shall first briefly review the FETI/FETI-DP based domain decomposition methodology adapted to the solution of variational inequalities with dissipative term such as those that describe equilibrium of a system of bodies in mutual contact with a given (Tresca) friction. As a result, we shall obtain convex quadratic programming problems with bounds and equality constraints. Using the known results concerning the solution of linear elliptic boundary value problems, we shall show that the condition number of the Hessian of the quadratic form is independent on the discretization parameter h. Combining these results with our theoretical results concerning optimal algorithms for the solution of bound and/or equality constrained quadratic programming problems, we shall obtain results on scalability of our FETI-DP and FETI based algorithms. Finally we shall give results of numerical experiments to show that the qualitative properties of our algorithms may be observed in practice.

Maksymilian Dryja, Marcus Sarkis, WPI-USA and IMPA-Brazil

A Neumann-Neumann method for discontinuous Galerkin discretization of elliptic equations
Location: S1 **Date:** Tuesday, July 4, 17:30 – 17:55

A discontinuous Galerkin (DG) discretization of Dirichlet problems for elliptic equations is considered. A region where the problem is imposed is a union of substructures with quasi-uniform triangulation in each of them. For this discretization a Neumann-Neumann (N-N) is designed and analyzied. This method is very well known for the standard finite element discretizations. A goal is to extend this method for DG discretization of elliptic problems. The coarse space is defined using a partitining of unity. A rate of convergence of the method is almost optimal. The method is very well suited for parallel computations.

Bernd Flemisch, Manfred Kaltenbacher, Barbara Wohlmuth

Efficient solution strategies for coupled problems in acoustics
Location: S1 **Date:** Thursday, July 6, 17:00 – 17:25

The propagation of sound waves over large regions is often the result of sources concentrated within a comparably small area. These sources can be given, e.g., by the vibration of structures, or simply appear as a right hand side of the wave equation modeling the sound propagation. In both cases, it is natural to decompose the global domain in a source domain and a domain of propagation in a non-overlapping manner. For the first case, this results in a coupled elasto-acoustic problem with different model equations in both subregions, for the second case, it yields a coupled acoustic-acoustic problem with a non-trivial source term in the smaller subdomain.

The discretization by means of finite elements demands a grid of high resolution in the source domain, whereas for the domain of propagation, a relatively coarse mesh is sufficient. Therefore, it is advantageous to use on each subdomain the grid best suited for the corresponding decoupled subproblems, yielding possibly non-matching grids on the interface common to both subdomains. While on each subdomain the choice of the ideal discretization principally yields a good approximation of the quantities of interest within this subdomain, it remains to construct numerically robust transmission operators for the information transfer between the non-matching grids.

In this talk, we develop corresponding non-conforming discretization methods and investigate their quality. In particular, we choose different possibilities for the excitation of the structure, e.g., by the piezo-electric effect, as well as different model equations for the elasto-dynamic response, including linear and nonlinear material laws. A central issue is the presentation of solution strategies for potentially resulting linear-nonlinear coupled problem settings.

Axel Klawonn, Oliver Rheinbach

Extending the scalability of FETI-DP: from exact to inexact algorithms
Location: S1 **Date:** Monday, July 3, 17:00 – 17:25

Dual-primal FETI methods are among the most severely tested domain decomposition methods for the solution of partial differential equations. With the advent of massively parallel computers with up to 100,000 processors new concepts are necessary to maintain the good scalability of these iterative methods.

In this talk, a framework for the algorithmic design of dual-primal FETI methods will be discussed focusing on the construction of scalable domain decomposition methods on massively parallel machines; convergence estimates and preliminary numerical results will also be presented.

Y. Maday, F. Magoulès

Improved ad hoc interface conditions for the FETI domain decomposition method tuned to highly heterogeneous media
Location: S1 **Date:** Thursday, July 6, 18:00 – 18:25

In the original version of the FETI domain decomposition method, a Neumann problem is solved on each sub-domain. Later on, in a variant of this method, an additional Dirichlet problem is solved exactly on each sub-domain. Unfortunately, for the Laplace equation, when dealing with arbitrary mesh partitioning, it may appear that one or more sub-domains are not attached to an external boundary condition. This leads to so-called floating sub-domains, and to non well-posed Neumann sub-problems. An additional procedure for the detection of the rigid body motions is thus mandatory to compute the solution inside these floating sub-domains. Incidently, this extra work for the detection can be cast in a coarse grid preconditioner that allows to give the scalability of the method. For the Helmholtz equation, when using the FETI method, local resonance frequencies may appear in some sub-domains. A remedy to this problem, consists of defining a relative fine coarse grid, similar to the case of floating sub-domains for the Laplace equation. Another solution consists of changing the Neumann interface conditions by Robin interface conditions, with complex coefficients. Using complex coefficients shifts the eigenvalues of the partial differential operator to the complex plane, and avoids any local resonance frequencies.

In this talk an original variant of the FETI domain decomposition method is introduced for heterogeneous media. This method uses *new real absorbing interface conditions* in place of the Neumann interface conditions defined in the classical FETI method. The optimal convergence properties of the classical FETI method and of its variant are then demonstrated, both in the case of homogeneous and heterogeneous media. The design of novel and efficient *real absorbing interface conditions* is then investigated, derived and analyzed. Several numerical results illustrate the robustness and the efficiency of the FETI method equipped with these new interface conditions upon several parameters. The results seem very promising in the case of heterogeneous media.

[1] C. Farhat and F.X. Roux, *Implicit parallel processing in structural mechanics*, North-Holland, eds. J. Tinsley Oden. 1994. 2, 1–124

[2] C. Farhat, P.S. Chen and F.-X. Roux, *The dual Schur complement method with well-posed local Neumann problems: regularization with a perturbed Lagrangian formulation*, SIAM Journal Scientific Statistic Computing. 1993. 14, 752–759

[3] C. Farhat, A. Macedo, M. Lesoinne, F.-X. Roux, F. Magoulès and A. de la Bourdonnaye, *Two-level domain decomposition methods with Lagrange multipliers for the fast iterative solution of acoustic scattering problems*, Computer Methods in Applied Mechanics and Engineering. 2000. 184(2), 213–240

[4] Y. Maday and F. Magoulès, *Non-overlapping additive Schwarz methods tuned to highly heterogeneous media*, Comptes Rendus à l'Académie des Sciences, in press. 2005. 341(11), 701–705

[5] Y. Maday and F. Magoulès, *Optimized Schwarz methods without overlap for highly heterogeneous media*, Computer Methods in Applied Mechanics and Engineering, in press

Clark R. Dohrmann, Jan Mandel, Bedrich Sousedik

Multilevel BDDC

Location: S1 **Date:** Monday, July 3, 16:30 – 16:55

We present the formulation and new condition number bounds for a multilevel version of the BDDC algorithm by Dohrman. The condition number bound grows polylogarithmically with the ratio of the substructure sizes between levels, but it is not bounded independently of the number of levels. Numerical results show that this may indeed occur.

The condition number bounds are based on a new multilevel algebraic theory suitable for nested substructuring methods.

Günther Of, Olaf Steinbach

An all-floating formulation of the BETI method

Location: S1 **Date:** Tuesday, July 4, 18:00 – 18:25

The combination of non-overlapping domain decomposition methods with fast boundary element methods gives an efficient simulation tool to handle coupled boundary value problems with piecewise constant coefficients. The Boundary Element Tearing and Interconnecting (BETI) methods have recently been introduced by Langer and Steinbach as boundary element counterparts of the well-established Finite Element Tearing and Interconnecting (FETI) methods. The FETI and BETI preconditioners are robust with respect to jumps in the coefficients of the elliptic partial differential operator.

Here, the BETI method is applied to problems in linear elastostatics. An efficient parallel iterative solver is provided by a twofold saddle point formulation. Efficient preconditioners are used for the global system and the local boundary integral operators which are realized by the use of the Fast Multipole Method. The BETI preconditioner, which can also be used in FETI methods, is based on the spectral equivalence of the hypersingular operator and the Steklov Poincare operator. This approach is more efficient than the application of the local Steklov-Poincare operators, i.e. the solution of local Dirichlet problems.

The treatment of floating subdomains, where the kernels of the local Steklov Poincare operators have to be eliminated by a stabilization and a global projection, is more difficult than in the case of the Laplacian. Therefore, a new all-floating formulation is presented for the BETI method. This formulation unifies and simplifies the treatment of floating and non-floating subdomains. In the numerical examples, this formulation provides a faster solution than the standard BETI formulation.

This is a joint work with U. Langer and W. Zulehner and was supported by the German Research Foundation (DFG) unter the SFB 404 'Multifield Problems in Continuum Mechanicsánd the Austrian Academy of Sciences within the Radon Institute for Computational and Applied Mathematics.

LUCA PAVARINO, RICHARD PASQUETTI, FRANCESCA RAPETTI, ELENA ZAMPIERI

Balancing Neumann-Neumann methods for Fekete spectral elements
Location: S1 **Date:** Tuesday, July 4, 16:30 – 16:55

We continue our investigation of domain decomposition preconditioners for triangular / tetrahedral spectral element (TSEM, see e.g. [1]) discretizations of elliptic problems. While TSEM can be used in highly complex geometries using unstructured meshes, the resulting discrete systems are more ill-conditioned than with classical Gauss-Lobatto-Legendre spectral elements (SEM). Moreover, the spectral equivalence between the SEM and the associated finite element stiffness matrices is no longer valid. These facts make the design of efficient TSEM preconditioners a more challenging issue. In our previous work [2], we focused on overlapping Schwarz methods for Fekete TSEM, obtaining optimal and scalable methods only in the computationally expensive case of generous overlap between subdomains. Here we consider instead nonoverlapping methods for the Fekete Schur complement, employing a Neumann-Neumann type preconditioner based on the solution of local Neumann problems on each subdomain and, in the Balancing Neumann-Neumann version, on the additional solution of a coarse problem with a few unknowns per subdomain. Several numerical results show that, in spite of the more severe ill-conditioning, the condition number of the Fekete preconditioned operator satisfies the same polylogarithmic bound as in the classical SEM case.

[1] R. PASQUETTI AND F. RAPETTI, *Spectral element methods on triangles and quadrilaterals: comparisons and applications*, J. Comput. Phys., 198:349–362, 2004

[2] R. PASQUETTI, L. F. PAVARINO, F. RAPETTI, E. ZAMPIERI, *Overlapping Schwarz preconditioners for Fekete spectral elements*, in the Proceedings of DD16, O. B. Widlund et al. Editors, Springer LNCSE, 2006. To appear

AXEL KLAWONN, LUCA PAVARINO, OLIVER RHEINBACH

FETI-DP and BDDC for higher order methods
Location: S1 **Date:** Tuesday, July 4, 16:00 – 16:25

Nonoverlapping domain decomposition methods of the FETI-DP and BDDC type have been widely in use. We present sequential and parallel performance results of FETI-DP and BDDC algorithms. This includes an inexact variant of the FETI-DP method for spectral elements.

OLOF WIDLUND

Extending the theory for iterative substructuring algorithms to less regular subdomains
Location: S1 **Date:** Thursday, July 6, 16:30 – 16:55

Assumptions on the regularity of the subdomains are routinely made in developing bounds for the condition numbers of a variety of iterative substructuring methods such as those in the FETI and BDDC families. A number of technical tools have thus been developed for subregions which are unions of a few shape-regular large tetrahedra. In this talk, some of these tools will be extended to subregions such as those which arise when using mesh partitioners.

FRANÇOIS-XAVIER ROUX, JUVIGNY XAVIER

FETI-H approach for coupling finite elements and boundary elements in acoustics
Location: S1 **Date:** Thursday, July 6, 17:30 – 17:55

Solving an external acoustic scattering problem, using a Finite Element method (FEM), requires that the external mesh extends far away from the obstacle, covering any observation points, which is impossible. The Boundary Element method (BEM) makes it possible to compute the scattering sound wave at any observation point in the external space. On the other hand, BEM requires an uniform sound speed in the external space or an homogeneous material for the obstacle, as opposed to the FEM method. Coupling the BEM and FEM methods achieves the advantages of both formulations. FEM formulation is applied around the obstacle and BEM formulation on a fictive surface Γ which includes the obstacle and is used as an interface between FEM and BEM formulation. This fictive surface could be extruded from the obstacle surface mesh or could be a surface revolution. The interface problem is solved thanks to a Feti-H formulation with a Robin condition on Γ. An orthodir solver computes the solution of the linear algebra problem issued from the FETI-H formulation. This decomposition method is validated with the acoustic scattering problem around a sphere by comparing the solution with the analytic solution.

M06

Multiphysics problems

Organized by Ronald Hoppe and Ralf Kornhuber

Coupled heterogeneous phenomena are not an exception but the rule in advanced numerical simulations of fluid dynamics, microelectronics, hydrodynamics, haemodynamics, electrodynamics or acoustics. Mathematical understanding and efficient numerical solvers become more and more important.

The aim of this minisymposium is to bring together scientists working in this field to report about recent developments.

Heiko Berninger, M. Discacciati, R. Kornhuber, O. Sander,

On a method of Robin-type for the Richards equation in heterogeneous soil
Location: Bürglsaal **Date:** Monday, July 3, 17:00 – 17:25

The Richards equation is a doubly nonlinear elliptic - parabolic pde describing saturated - unsaturated groundwater flow. We assume the porous medium to be heterogeneous, i.e. constituted by subdomains with different soil types. Then the nonlinearities depending on the soil parameters change discontinuously across the interfaces between these subdomains. In our time - discretization of the Richards equation, the gravitational part is taken explicitly. Then Kirchhoff transformation, applied separately in the subdomains, leads to local convex minimization problems. These local problems can be treated efficiently and robustly using monotone multigrid [2]. Nonlinear nonoverlapping domain decomposition like the Dirichlet–Neumann or the Robin method provides a coupling of these problems. Here we focus on the Robin method. We present a nonlinear Steklov - Poincaré theory for a method of Robin - type applied to the Richards equation and related problems. This leads us to a convergence result for the Richards equation in one space dimension. Finally, numerical results show the efficiency of the Robin method for our problem in higher dimensions.

[1] H. Berninger, *Domain Decomposition Methods for Problems with Jumping Nonlinearities and Application to the Richards Equation*, Dissertation, FU Berlin, in preparation

[2] R. Kornhuber, *On Constrained Newton Linearization and Multigrid for Variational Inequalities*, Numer. Math. 91 (2002), 699–721

Suncica Canic, Giovanna Guidoboni, Andro Mikelic, Josip Tambaca,

On the fluid-structure interaction in blood flow
Location: Bürglsaal **Date:** Tuesday, July 4, 16:30 – 16:55

We will focus on a fluid-structure interaction problem arising in modeling blood flow through compliant (elastic/viscoelastic) arteries. The model is based on the viscous incompressible Navier-Stokes equations modeling blood flow in medium-to-large arteries, coupled with the elastic/viscoelastic Koiter shell equations modeling the dynamics of arterial walls. The resulting problem is of hyperbolic-parabolic type coupling wave propagation in arterial walls with the flow of a viscoelastic incompressible (Newtonian) fluid. Due to the hyperbolic nature of arterial wave propagation and due to the fact that the density of arterial walls is close to the density of the fluid, this fluid-structure interaction problem suffers from various difficulties associated with the lack of smoothing in the iteration procedures typically employed in the theoretical and numerical solution methods. To understand the main underlying difficulties, and to provide a model which can be efficiently solved numerically using one-dimensional methods, we derived a two-dimensional ("almost" one-dimensional) effective model obtained from the three-dimensional, axially symmetric problem by using homogenization theory for porous media flows. The resulting, effective model, is of Biot-type with memory. It captures the main features of blood flow in elastic/viscoelastic arteries. A comparison between the numerical simulations of the effective equations and the experimental measurements performed at the Texas Heart Institute in Houston showed excellent agreement. In particular, the viscoelastic arterial wall model captured well the hysteresis behavior of human and canine arteries. We will discuss the existence of a solution to the effective free-boundary problem and the difficult challenges and new insights that it brings towards the understanding of the fluid-structure interaction in blood flow. Collaborators include: A. Mikelic (University of Lyon 1, FR, J. Tambaca, University of Zagreb, Croatia, G. Guidoboni, UH, Dr. Z Krajcer, Texas Heart Institute, Dr. C. Hartley, Baylor College of Medicine, and Dr. D. Rosenstrauch, Texas Heart Institute.

Marco Discacciati

Iterative solution methods for a magnetohydrodynamic problem in velocity-current formulation
Location: Bürglsaal **Date:** Monday, July 3, 16:00 – 16:25

In this presentation we consider a magnetohydrodynamic problem in velocity-current formulation involving the Stokes equations and Ohm's law in the computational fluid region together with an external unknown magnetic field. Such coupled models arise in several industrial applications, e.g. in metal production.

In this talk we will outline the mathematical and numerical analysis of this coupled problem and we will introduce a suitable conforming finite element discretization. Then, we will illustrate possible decoupled iterative solution methods with particular concern on the skew-symmetric saddle-point problem arising in the fluid domain. Some numerical tests will be presented.

Jürgen Geiser

Time- and space-decomposition methods as fast adaptive solvers: theory and applications in fluid dynamics
Location: B2 **Date:** Monday, July 3, 17:00 – 17:25

In this paper we consider time- and space-decomposition methods for parabolic equations related to multi-physics problems. The time decomposition methods are based on the operator - splitting methods and we concentrate on an iterative decomposition method, see [2], [3]. For the space decomposition methods we present an overlapping Schwarz wave form relaxation method for overlapped sub-domains, see [1]. We derive the theory for a system of convection-diffusion-reaction equations and present the accuracy and the efficiency of coupling the time- and space-decomposition-methods. The exactness and the efficiency of the methods are investigated through solutions of different model problems of scalar and weakly coupling systems of convection-reaction-diffusion equation. Finally we discuss the applications to multi-dimensional problems and taken to account a parallelization of the methods.

[1] D. Daoud and J. Geiser, *Fractional-Splitting and Domain-Decomposition Methods for Parabolic Problems and Applications*, Preprint No. 1096 of the Weierstrass Institute for Applied Analysis and Stochastics, Berlin, Germany, January 2006

[2] J. Geiser and J. Gedicke, *Iterative Operator - Splitting Methods with higher order Time-Integration Methods and Applications for Parabolic Partial Differential Equations*, Preprint No. 2006-10 of Humboldt University of Berlin, Department of Mathematics, Germany, April 2006

[3] J.Geiser and Chr.Kravvaritis, *Weighted Iterative Operator-Splitting Methods for stiff problems and applications*, Preprint No. 2006-11 of Humboldt University of Berlin, Department of Mathematics, Germany, April 2006

Ronald Hoppe

Modeling and simulation of piezoelectrically agitated acoustic streaming on microfluidic biochips

Location: Bürglsaal **Date:** Monday, July 3, 17:30 – 17:55

Biochips, of the microarray type, are fast becoming the default tool for combinatorial chemical and biological analysis in environmental and medical studies. Programmable biochips are miniaturized biochemical labs that are physically and/or electronically controllable. The technology combines digital photolithography, microfluidics and chemistry. The precise positioning of the samples (e.g., DNA solutes or proteins) on the surface of the chip in picoliter to nano liter volumes can be done either by means of external forces (active devices) or by specifc geometric patterns (passive devices). The active devices which will be considered here are nano liter fluidic biochips where the core of the technology are nano pumps featuring surface acoustic waves generated by electric pulses of high frequency. These waves propagate like a miniaturized earthquake (nanoscale earthquake), enter the fluid filled channels on top of the chip and cause an acoustic streaming in the fluid which provides the transport of the samples. The mathematical model represents a multiphysics problem consisting of the piezoelectric equations coupled with multiscale compressible Navier-Stokes equations that have to be treated by an appropriate homogenization approach. We discuss the modeling approach and present algorithmic tools for numerical simulations as well as visualizations of simulation results.

Dietrich Braess, Bernd Flemisch, Manfred Kaltenbacher, Barbara Wohlmuth

Advanced coupling of structural mechanics and acoustics in time and frequency domain
Location: Bürglsaal **Date:** Tuesday, July 4, 16:00 – 16:25

In many technical applications a sensor and/or an actuator is immersed in an acoustic fluid, e.g. ultrasound transducers for nondestructive testing as well as medical diagnostic and therapy, ultrasound cleaning, electrodynamic loudspeakers, capacitive microphones, etc. For many applications, the numerical simulation of the actuator mechanism within the structure is quite complex, since in most cases we have to deal with a nonlinear coupled problem (e.g. electrostatic-mechanical principle used in many micro-electromechanical systems), where in addition to the nonlinear coupling terms each single field is nonlinear (e.g., geometric nonlinearity in mechanics, moving body problem in the electrostatic field). Furtheron, in most cases the discretization within the structure has to be much finer than the one we need for the acoustic wave propagation in the fluid. In addition, the computation of the acoustic field needs special treatment of the boundary conditions in order to avoid spurious reflections. Furthermore, since the acoustic sound/noise is in most cases generated by thin mechanical vibrating structures, locking effects arise and have to be treated appropriately.

Within our contribution we will address the above mentioned challenges and present numerical methods for the efficient computation of coupled mechanical-acoustic problems. In special, we will present nonmatching grid techniques applying mortar finite elements for the coupling between the mechanical and acoustic field, perfectly matched layer (PML) techniques for treating the acoustic boundary, and the computation of thin mechanical structures by a special decomposition and scaling of the shear and bending terms.

Omer F. Alpak, Tarek M. Habashy, Dzevat Omeragic, Joachim Schöberl

Joint electromagnetic-pressure-fluid flow modeling and inversion for oilfield applications
Location: Bürglsaal **Date:** Monday, July 3, 16:30 – 16:55

We review algorithms for joint electromagnetic (EM), pressure, fluid flow modeling and inversion for oilfield applications. The integrated petrophysical evaluation procedures uses EM measurements acquired with array induction tool or DC resistivity permanent sensors and pressure measurements acquired with a multi-probe formation tester. This approach is used to build a refined layered formation model with estimates of anisotropic permeability and porosities.

A commercial finite-difference multiphase fluid-flow reservoir simulator is used for simulation of mud-filtrate invasion. Physics of multi-phase fluid flow and EM induction in porous media is coupled through an appropriate saturation equation, where nonlinear saturation functions of relative permeability and capillary pressure are parametrically represented. Spatial distributions of fluid saturations are converted to electric conductivities, subsequently used to simulate the EM responses of resistivity tools. The EM simulators could be based on finite-difference or finite- element method. We will discuss practical aspect of using domain-decomposition options in both fluid-flow and finite-element EM simulators.

Numerical examples are shown for vertical borehole and axisymmetric models. The joint inversion reduces the non-uniqueness by honoring two sets of complementary measurements, leading to more accurate estimate of permeability and conductivity compared to separate inversion of each data type. We will also show some preliminary results related to high-angle and horizontal well applications, where invasion shape is complex and requires computationally intensive 3D modeling. We evaluated the influence of petrophyisical parameters on fluid saturation and sensitivity of EM induction tool responses to complex saturation distribution, and use of simple parametric models for measurement interpretation. This is a joint work with U. Langer and W. Zulehner and was supported by the German Research Foundation (DFG) unter the SFB 404 'Multifield Problems in Continuum Mechanicsánd the Austrian Academy of Sciences within the Radon Institute for Computational and Applied Mathematics.

Ralf Kornhuber, Rolf Krause, Oliver Sander

Multi-dimensional coupling in a human knee model
Location: Bürglsaal **Date:** Tuesday, July 4, 17:00 – 17:25

Our work is motivated by the biomechanical coupling of bones with long slender objects like tendons and ligaments in human joints. Whereas the former will be modelled using 3D linear elasticity, for the latter we will use 1D Cosserat rods. The correct coupling conditions are derived by equating the work done on the interface by the 3D object with the work done by the small cross-section at the end of the rod.

The resulting system is a coupled minimization problem involving the sum of a quadratic and a smooth, nonconvex energy functional. These kinds of optimization problems can be solved efficiently by a structured trust-region solver. A monotone multigrid method is used as the inner solver in order to ensure optimal complexity solutions of the quadratic programs.

An additional problem is the handling of the multibody contact between the bones. We show how this can be done efficiently using the well-known mortar-element approach by Wohlmuth and Krause.

Erik Burman, Paolo Zunino

Domain decomposition methods based on weighted interior penalties
Location: Bürglsaal **Date:** Tuesday, July 4, 18:00 – 18:25

We propose a domain decomposition method for advection-diffusion-reaction equations based on Nitsche's transmission conditions. The advection dominated case is stabilized using a continuous interior penalty approach based on the jumps in the gradient over element boundaries. We prove the convergence of the finite element solutions of the discrete problem to the exact solution and we propose a parallelizable iterative method. The convergence of the resulting domain decomposition method is proved and this result holds true uniformly with respect to the diffusion parameter. The numerical scheme that we propose here can thus be applied straightforwardly to diffusion dominated, advection dominated and hyperbolic problems. Some numerical examples are presented in different flow regimes showing the influence of the penalty parameters on the performance of the iterative method and we compare with some other domain decomposition techniques for advection–diffusion equations. Furthermore, this work is extended to the generalized Stokes problem. In particular, we set up and analyze a domain decomposition method for linear incompressible flows that can automatically treat the coupling between a free fluid and a porous medium as the limit case where the viscosity vanishes in a subregion of the domain.

M07

Optimized Schwarz methods: promises and challenges
Organized by Lahcen Laayouni

Recent developments on Schwarz methods have the aim to improve the performance and speed up the rate of convergence of these methods. Those improvements are based essentially on imposing new types of transmission conditions involving different combinations of solution, normal and tangential derivatives, rather than exchanging only solutions between subdomains. As promised, optimized Schwarz methods have given great enhancements to classical Schwarz methods and rigorous Fourier analysis on strip decompositions have been done to confirm this. Big challenges are now to extend the performances of optimized Schwarz methods to higher dimensional problems and more complicated systems. In the present mini-symposium we will consider some answers to different aspects of those challenges.

Victorita Dolean, Frederic Nataf

A new domain decomposition method for the compressible Euler equations
Location: B2 **Date:** Thursday, July 6, 17:30 – 17:55

In this work we design a new domain decomposition method for the Euler equations in 2 dimensions. The starting point is the equivalence with a third order scalar equation to whom we can apply an algorithm inspired from the Robin-Robin preconditionner for the convection-diffusion equation. Afterwards we translate it into an algorithm for the intial system and prove that at the continuous level and for a decomposition into 2 sub-domains, it converges in 2 iterations. This property cannot be conserved strictly at discrete level and for arbitrary domain decompositions but we still have numerical results which confirm a very good stability with respect to the various parameters of the problem (mesh size, Mach number, ...).

Olivier Dubois

Optimized Schwarz methods for problems with discontinuous coefficients
Location: B2 **Date:** Thursday, July 6, 17:00 – 17:25

The optimized Schwarz methods are usually derived using a model problem with constant coefficients. The results can then be used successfully in practice for more general domains, and coefficients varying smoothly across interfaces. However, in many applications, the differential equation has large jumps in the coefficients (for example when the computational domain consists of different materials). For such cases, it is very natural to consider a nonoverlapping domain decomposition, where interfaces correspond to where the coefficents are discontinuous, and use a Schwarz iteration.

In this work, we derive optimized transmission conditions for problems with piecewise constant coefficients on the subdomains. We solve the min-max problem to obtain either explicit formulas for the optimized parameters, or a simple characterization of the solution. In addition, we study the asymptotic behavior of the convergence for small mesh sizes, and for large jumps in the coefficients. Numerical experiments will illustrate the convergence results.

Lahcen Laayouni

Optimal and optimized domain decomposition methods for three-dimensional partial differential equations
Location: B2 **Date:** Thursday, July 6, 16:00 – 16:25

Many investigations have been devoted to optimal and optimized Schwarz methods to solve partial differential equations. Such methods differ from classical Schwarz methods by using more general transmission conditions to communicate between subdomains instead of exchanging only the value of solutions. Optimal and optimized Schwarz methods converge asymptotically faster than classical Schwarz methods and can be used for both overlapping and non-overlapping decompositions. Optimal Schwarz methods use non-local operators at the interfaces, and converge in a finite number of steps, but are highly expensive compared to classical Schwarz methods. Optimized Schwarz methods use local transmission conditions and converge uniformly much faster than classical Schwarz methods, at the same cost per iteration.

In this talk we will give the extension of optimal and optimized Schwarz methods to cover three-dimensional partial differential equations. As a model problem we consider the positive definite Helmholtz problem defined in the three-dimensional space. For this model we provide the non-local interface operators for which optimal Schwarz methods converge in finite number of steps. Then, we give the optimized local transmission conditions for which optimized Schwarz methods converge faster than classical Schwarz methods. We present numerical experiments to confirm the theoretical results.

Jean Côté, Martin J. Gander, Lahcen Laayouni, Abdessamad Qaddouri

Optimized Schwarz method with the Yin-Yang grid for the Shallow-Water Equations
Location: B2 **Date:** Thursday, July 6, 18:00 – 18:25

The composite "Ying-Yang" grid is singularity free and has quasi-uniform grid spacing.It is composed of two identical latitude/longitude orthogonal grid panels that are combined to cover the sphere with partial overlap on their boundaries. We are interested in solving the time-dependent system of Shallow-Water equations (SWEs) on the Yin-Yang grid by using the domain decomposition method. The SWEs are solved by using a semi-implicit and semi-Lagrangian time discretization on a staggered mesh. The resulting scalar elliptic equation for the geopotential height is solved using the optimized Schwarz method, with different types of transmission conditions, as preconditioner for Krylov methods or as iterative solver.

Amik St-Cyr

Performance of optimized Schwarz in a massively parallel next generation climate model
Location: B2 **Date:** Thursday, July 6, 16:30 – 16:55

To achieve scientifically significant integration rates, the modern generation of global atmospheric and ocean models employs semi-implicit time-stepping. The latter leads to a positive definite Helmholtz problem to invert at each time step *as fast as possible*. A recent paradigm shift in massively parallel supercomputers forces the exploitation of very large number of processors with reduced cache memory. The inner products present in any Krylov accelerator are global parallel communications that can be problematic at large processor counts. High-order element methods yield dense sub-blocks not suitable for small cache memory based systems. In this presentation, we show how to construct cache efficient high-order optimized Schwarz preconditioning and show its parallel performance in a general circulation model based on the spectral element method.

This work was partially supported by NSF CMG[a] grant 0222282 and the DOE[b] CCPP[c]. Computer time was provided by NSF MRI Grant CNS-0421498, NSF MRI Grant CNS-0420873, NSF MRI Grant CNS-0420985, NSF sponsorship of NCAR, the University of Colorado, and a grant from the IBM Shared University Research (SUR) program.

[a] National Science Foundation Collaborations in Mathematics and Geosciences
[b] Department Of Energy
[c] Climate Change Prediction Program

M08

Robust methods for multiscale PDE problems
Organized by Ivan Graham and Rob Scheichl

This minisymposium will focus on recent developments in analysis and implementation of preconditioners for elliptic problems with highly variable multiscale coefficients, including cases where the coefficient variation cannot be effectively resolved by a practical coarser mesh. Many examples arise, for example in deterministic and stochastic models in hydrogeology, and in oil reservoir modelling. Standard coarsening techniques based on polynomial interpolation do not work well for such problems and in this minisymposium we will focus on recently proposed better techniques, such as multiscale finite element coarsening, optimised interface preconditioners, deflation, and algebraic approaches which are designed to accommodate coefficient behaviour.

Luc Giraud

Robust algebraic two-level preconditioner for non-overlapping methods
Location: B1 **Date:** Monday, July 3, 16:00 – 16:25

In this talk, we will desribe robust two-level preconditioners for the Schur complement method. Numerical and parallel performances on academic and real life application problems will be reported.

Ivan Graham

Domain decomposition for multiscale PDEs
Location: B1 **Date:** Monday, July 3, 17:00 – 17:25

We consider overlapping two-level additive Schwarz preconditioners for low order finite element approximations of elliptic PDEs with highly variable coefficients. In contrast to standard analyses, we do not assume that the coefficients can be resolved by a coarse mesh. This situation arises often in practice, for example in the computation of flows in heterogeneous porous media, in both the deterministic and stochastic cases.

We perform a new analysis of the preconditioned matrix, which shows rather explicitly how its condition number depends on the variable coefficient in the PDE as well as on the coarse space and overlap parameters. These results explain why, with a good choice of subdomains and coarse space, the preconditioner can still be robust even for large coefficient variation inside domains.

We explore the use of low-energy coarse spaces constructed from multiscale finite elements and prove that these lead to robust preconditioners for a variety of binary (i.e. two-scale) media model problems. Numerical experiments show that this choice can lead to greatly improved performance over standard preconditioners also in the random coefficient case.

Markus Kirkilionis, Nicolas Neuss, Greg A. Pavliotis

Multiscale simulation of diffusion and absorption in chloroplasts
Location: B1 **Date:** Monday, July 3, 18:00 – 18:25

Protein translocation is a necessary biological process in cells structured by compartments. As a model for a protein translocation process we consider the chloroplasts of plant cells. Chloroplasts have an own genome, but not all proteins needed for example in photosynthesis are produced inside the chloroplast. A large set of such proteins still has to be imported into the thylakoids (where the actual photosynthesis is taking place) from the cytoplasm of the plant cell. In this contribution, we model this translocation process by diffusion through a complex medium with absorption occuring at the boundary of a complex inlay. The direct numerical simulation of is then demanding because of the intricate structure of the boundary. As a remedy, we present a homogenization approach where we replace nonlinear absorption at the boundary of the porous structure by a nonlinear sink term. We will estimate the modelling error numerically, and also demonstrate the validity of these estimates by numerical experiments.

Robert Scheichl, Eero Vainikko

Robust aggregation-based coarsening for multiscale PDEs
Location: B1 **Date:** Monday, July 3, 17:30 – 17:55

We study two-level overlapping domain decomposition preconditioners with coarse spaces obtained by smoothed aggregation in iterative solvers for finite element discretisations of second-order elliptic problems. We are particularly interested in the situation where the diffusion coefficient (or the permeability) α is highly variable throughout the domain. Our motivating example is Monte-Carlo simulation for flow in rock with permeability modelled by lognormal random fields. By using the concept of strongly-connected graph r-neighbourhoods (suitably adapted from the algebraic multigrid context) we design a two-level additive Schwarz preconditioner that is robust to strong variations in α as well as to mesh refinement. We give upper bounds on the condition number of the preconditioned system which do not depend on the size of the subdomains (not available previously in the literature) and make explicit the interplay between the coefficient function and the coarse space basis functions in this bound. In particular, we are able to show that the condition number can be bounded independent of the ratio of the two values of α in a binary medium even when the discontinuities in the coefficient function are not resolved by the coarse mesh. Our numerical results show that the bounds with respect to the mesh parameters are sharp and that the method is indeed robust to strong variations in α. We compare the method to other preconditioners (aggregation-type AMG and classical additive Schwarz) as well as to a sparse direct solver, and show its superiority over those methods for highly variable coefficient functions α.

Karl Scherer

Robust norm equivalencies and optimal preconditioners
Location: B1 **Date:** Monday, July 3, 16:30 – 16:55

In additive multilevel methods norm equivalencies for the bilnear forms associated with elliptic operators play a decisive role. The constants in the equivalencies are crucial for the stability of iteration methods for the stiffness matrix in the corresponding Ritz-Galerkin equations, thus for the robustness of the numerical method. We adress this question first for the simple diffusion problem and prove that the lower bound is completely independent of the diffusion coefficient whereas the upper bound involves only a weak condition related to the Muckenhoupt classes in harmonic analysis. The results are then extended to the anisotropic case and the Helmholtz -problem.

M09

Subspace correction methods

Organized by Ralf Hiptmair, Ralf Kornhuber and Jinchao Xu

Subspace correction methods are well established as a unifying framework for multigrid and domain decomposition. It also serves as a powerful tool both for the construction and the analysis of efficient iterative solvers for discretized partial differential equations.

This minisymposium will provide an overview on recent results in this field with special emphasis on linear and nonlinear systems.

Ralf Forster, Ralf Kornhuber, Karin Mautner

Fast and reliable pricing of American options with local volatility

Location: Bürglsaal **Date:** Thursday, July 6, 16:30 – 16:55

We consider the parabolic obstacle problem with variable coefficients appearing in the Black-Scholes equations with local volatility when evaluating American put options in mathematical finance. By suitable transformations we symmetrize the discretized problem to solve it by multigrid methods. Real-life data were used for the parameters and adapted carefully to the transformed problem. Finally we present numerical results to underline the convenience of this method within this setting.

Carsten Gräser, Ralf Kornhuber

Non-smooth Newton methods for set-valued saddle point problems

Location: Bürglsaal **Date:** Thursday, July 6, 16:00 – 16:25

We present a new class of preconditioners for Uzawa iterations as applied to saddle point problem with additional inequality constraints. The sequence of preconditioners is based on the linear Schur complements associated with successive approximations of the coincidence set. Each step of the preconditioned Uzawa iteration requires the (approximate) solution of an obstacle problem and a linear saddle point problem which both are performed by multigrid methods. A global convergence proof of the resulting iterative scheme is based on a reinterpretation in terms of non-smooth Newton-type descent method for an associated unconstrained convex problem. As expected from our theoretical findings we found superlinear convergence and finite termination in our numerical experiments.

Ralf Hiptmair, G. Widmer, J. Zou

Auxiliary Space Preconditioning in $H(\mathbf{curl})$

Location: Bürglsaal **Date:** Thursday, July 6, 18:00 – 18:25

We adapt the principle of auxiliary space preconditioning as presented in [2] to $H(\text{curl})$-elliptic variational problems discretized by means of edge elements. The algorithm can be analyzed within the abstract framework of subspace correction. Employing a Helmholtz-type splitting of edge element vector fields we can establish asymptotic h-uniform optimality of the preconditioner defined by our auxiliary space method. Numerical experiments in two dimensions demonstrate the excellent pre-asymptotic behavior of the method.

[1] R. Hiptmair, G. Widmer, and J. Zou, *Auxiliary space preconditioning in $H_0(curl, \Omega)$*, Numer. Math., 103 (2006), pp. 435-459

[2] J. Xu, *The auxiliary space method and optimal multigrid preconditioning techniques for unstructured grids*, Computing, 56 (1996), pp. 215–235

Qiya Hu

A new kind of multilevel preconditioner for interface operator arising from domain decomposition

Location: Bürglsaal **Date:** Thursday, July 6, 17:00 – 17:25

In this talk we report a new multilevel technique for preconditioning interface operator arising from non-overlapping domain decomposition method. This multilevel technique is based on a multilevel domain decomposition to the interface, and does not depend on nested triangulations on the interface (or the underlying domain). The corresponding multilevel preconditioner not only possesses the nearly optimal convergence but also has the almost optimal computational complexity.

Zhiming Chen, Long Wang, Weiying Zheng

An adaptive multilevel method for time-harmonic Maxwell equations with singularities
Location: Bürglsaal **Date:** Thursday, July 6, 17:30 – 17:55

In this talk, we develop an adaptive edge finite element method based on reliable and efficient residual-based a posteriori error estimates for low-frequency time-harmonic Maxwell's equations with singularities. The resulting discrete problem is solved by the multigrid preconditioned minimum residual iteration algorithm. We demonstrate the efficiency and robustness of the proposed method by extensive numerical experiments for cavity problems with singular solutions which includes, in particular, scattering over screens.

M10

Time DD methods for evolution problems
Organized by Martin Gander

Time Domain Decomposition methods are methods which decompose the time dimension of an evolution problem into time-subdomains, and then compute the solution trajectory in time simultaneously in all the time subdomains using an iteration. The advent of the parareal algorithm by Lions, Maday and Turinici in 2001 sparked renewed interest in these methods, and there are now several convergence results available for them. In particular, these methods exhibit superlinear convergence on bounded time intervals.

While the speedup with parallelization in time is often less impressive than with parallelization in space, parallelization in time is for problems with few spatial components often the only option, if results in real time need to be obtained. This reasoning also led to the name parareal (parallel in real time) of the new algorithm from 2001.

Guillaume Bal

Symplectic parareal
Location: B2 **Date:** Monday, July 3, 16:00 – 16:25

The parareal algorithm allows one to parallelize evolution equations by acting as a prediction correction scheme. The coarse prediction step is sequential while the accurate correction step can be computed in parallel. The discrepancy between coarse and accurate calculations generates jumps that need to be added sequentially to the discrete solution. This addition step looses the symplectic structure that both the coarse and accurate schemes may posess. We will consider methods that address this issue.

Jürgen Geiser

Time-decomposition methods for parabolic problems: convergence results of iterative splitting methods
Location: Bürglsaal **Date:** Tuesday, July 4, 17:30 – 17:55

In this paper we consider time-decomposition methods and present complicate model-problems as benchmark-problems to study the numerical analysis of the proposed methods. For the time-decomposition methods we discuss the iterative operator - splitting methods with respect to the stability and consistency. The main ideas are considering the Taylor-expansion of time and nonlinear operators and derive the errorestimates.

The stability analysis is based on the A-stability of ordinary-differential equations and one could see the importance of including weighted parameters to relax the iterative operator - splitting methods. The exactness and the efficiency of the methods are investigated through solutions of nonlinear model problems of parabolic differential equations, for exampler systems of convection-reaction-diffusion equation. Finally we discuss the future works and the applications in real-life applications.

D. Crann, A. J. Davies, Choi-Hong Lai

A two-level time domain algorithm for the solution of nonlinear transient parabolic problems with applications
Location: B2 **Date:** Monday, July 3, 18:00 – 18:25

Many engineering and applied science problems required the solutions of nonlinear diffusion equations where the nonlinear feature usually comes with the material properties or the conductivity. In the case of unsteady problems a time-marching scheme, usually with time step length restrictions, is employed in any temporal integration procedure. These restrictions are usually due to stability criteria of an explicit scheme or the truncation errors of an implicit scheme in approximating the temporal derivatives. Computing time of such numerical methods inevitably becomes significant. On the other hand fine grain parallelisation of time stepping becomes difficult and it is almost impossible to achieve a distributed/parallel algorithm that is able to yield a de-coupling of the original problem. There are also many problems which require solution details not at each time step of the time-marching scheme, but only at a few crucial steps and the steady state. Therefore effort in finding fine details of the solutions using many intermediate time steps is considered being wasted. Such effort becomes significant in the case of nonlinear problems where a linearisation process, which amounts to an inner iterative loop within the time-marching scheme, is required. It would be a significant save in computing time when the linearisation process and the time-marching scheme can both be done in parallel.

The idea of using a Laplace transform and its numerical inverse in the context of differential equations can be found from the literature for linear elliptic problems [1] [3], initially, and for the use with boundary element methods [3, 4]. There is also work in extending such method for nonlinear problems. The main purpose of such work has been the removal of the time stepping and combination of such method to boundary element methods as an efficient algorithm. More recently the method has also been extended to some nonlinear problems in flow through porous media [5] and financial computing [6]. The present paper further develop the idea into a time-domain parallel algorithm suitable for nonlinear parabolic partial differential equations. It involves two levels of temporal mesh. First the numerical solutions of a nonlinear time dependent parabolic problems, using the concept of a Laplace transform and its numerical inverse, are obtained on a coarser temporal mesh. This is essentially an application of the work proposed in [6]. The Laplace transform is applied to a linearisation of the time dependent nonlinear parabolic equation leading to a distributed algorithm of solving the resulting set of linear differential equations in the Laplace space. Solutions of the non-linear parabolic equation are then retrieved by means of an approximate inverse Laplace method. A time dependent non-linear parabolic problem is used to illustrate and compare the inverse Laplace method and a temporal integration method. The novel two-level time-domain is then introduced by combining the use of the inverse Laplace method and a temporal integration method. Numerical experiments are provided to examine the efficiency and accuracy of the new algorithm. Finally, discussions and conclusions are presented.

[1] D. Crann., *The Laplace transform: Numerical inversion for computational methods*, Technical Report No. 21, University of Hertfordshire, July (1996)

[2] D. Crann, A. J. Davies, C.-H. Lai, and S. W. Leong, *Time domain decomposition for European options in financial modelling*, Proceedings of the 10th International Conference on Domain Decomposition Methods, August 1997, Colorado. J. Mandel, C. Farhat, and X.-C. Cai, editors, Domain Decomposition Methods 10, American Mathematical Society, (1998)

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[4] S. Zhu, P. Satravaha and X. Lu, *Solving the linear diffusion quations with the dual reciprocity method in Laplace space*, Eng. Anal. Boundary Elements, 13, 1 - 10, 1994

[5] G. J. Moridis and D. L. Reddell, *The Laplace transform finite difference method for simulation of flow through porous media*, Water Resources Research , 27, 1873 - 1884, 1991

[6] C.-H. Lai, A. K. Parrott, S. Rout, *A distributed algorithm for European options with nonlinear volatility*, Computers and Mathematics with Applications, 49, 885 - 894, 2005

Yvon Maday, Julien Salomon, Gabriel Turinici

Parareal in time control for quantum systems
Location: B2 **Date:** Monday, July 3, 16:30 – 16:55

Following recent encouraging experimental results in quantum control, numerical simulations have known significant improvements through the introduction of efficient optimization algorithms. Yet, the computational cost still prevents using these procedures for high-dimensional systems often present in quantum chemistry. Using the parareal in time framework, we present here a time parallelization of these schemes which allows to reduce significantly their computational cost while still finding convenient controls.

Tarek Mathew, Marcus Sarkis, Christian E. Schaerer Serra

Time-parallel iterative algorithms for optimal control of parabolic equations
Location: B2 **Date:** Monday, July 3, 17:30 – 17:55

We consider the time-parallel solution of *large scale* linear-quadratic optimal control problems arising from the control of parabolic partial differential equations over a finite control horizon. The spatial discretization of such problems requires the optimal control of n coupled ordinary differential equations, where n can be quite large. Hence, it solution by conventional methods can be prohibitively expensive in terms of computational cost and memory requirements. By contrast, iterative algorithms compute the solution requiring only the storage of the primal and adjoint variables at each discrete time. Accordingly, we discretize in time the objective functional $J(\cdot)$ and the stiff system of ordinary differential equations, and introduce Lagrange multipliers (adjoint variables) to enforce the constraints, resulting in a large *saddle point* system of linear equations. We consider several domain decomposition preconditioned iterative algorithms motivated by the *Parareal* algorithm of Lions-Maday-Turinici. The first method is a multiple shooting method based on a decomposition of the time interval into subintervals. It updates the primal and adjoint variables on each subinterval and employs a coarse preconditioner to speedup convergence. The second consists of Usawa type algorithms for updating the adjoint variables on each time interval. Numerical results are presented for test problems.

Part IV

Abstracts of Contributed Talks

Yves Achdou, C. Sabot, N. Tchou

Boundary value problems in some ramified domains with a fractal boundary. Transparent boundary conditions

Location: S2 **Date:** Friday, July 7, 10:50 – 11:10

We consider some boundary value problems in self-similar ramified domains with a fractal boundary, with the Laplace and Helmholtz equations.

Both homogeneous and nonhomogeneous Neumann conditions on the fractal part of the boundary are considered. We give rigorous theoretical results extension and trace results, then we discuss the existence and uniqueness of the solutions.

Then, for homogeneous Neumann conditions, we propose transparent boundary conditions which permit the computation of the solutions in subdomains obtained by stopping the geometric construction after a finite number of steps. These conditions involve nonlocal Dirichlet to Neumann operator which can be computed by taking advantage of the geometrical self-similarity. A self similar finite element method is proposed and tested.

We compute numerically the spectrum of the Laplace operator in the irregular domain with Neumann boundary conditions, as well as the eigenmodes. The repartition of the eigenvalues is investigated. The eigenmodes are normalized by means of a perturbation method and the spectral decomposition of a compactly supported function is carried out. This enables us to solve numerically the wave equation in the self-similar ramified domain.

For nonhomogeneous problem, we propose a multiscale strategy taking advantage of the above-mentioned transparent conditions.

Torsten Adolph, Willi Schönauer

Automatic domain decomposition for a black-box PDE solver

Location: S1 **Date:** Tuesday, July 4, 11:15 – 11:35

We want to develop a tool to distribute automatically a given arbitrary 2D or 3D mesh equally among a given number of processors. First we sort the nodes by their x-coordinate locally on each processor, afterwards globally by a sophisticated algorithm where we make use of the message passing paradigm. This results in a one-dimensional domain decomposition that may also run over dividing lines. The elements are sent around in a ring shift afterwards, where each processor takes the necessary element information out of the current basket in each tact. To be able to execute the following solution of the system of PDEs purely local without communication, we also create an overlap, i.e. we also store on each processor the necessary nodes and elements of neighbouring processors. The re-sorting of refined meshes serves the purpose of load-balancing, and for the resulting matrix it serves as a kind of bandwidth optimizer.

Lori Badea

Additive multilevel Schwarz method for the constrained minimization of functionals in reflexive Banach spaces

Location: B1 **Date:** Friday, July 7, 11:15 – 11:35

In [L. Badea and J. Wang, “An additive Schwarz method for variational inequalities”, Math. Comp., 69, 232, pp. 1341–1354], an additive Schwarz method has been proposed for symmetric variational inequalities. Although this method do not assume a decomposition of the convex set according to the domain decomposition, the convergence proof is given only for the one-obstacle problems. In this paper, we prove that the method converges in a much more general framework, ie. we can apply it to the minimization of functionals over a enough general convex set in a reflexive Banach space. In the Sobolev spaces, the proposed method is an additive Schwarz method for the solution of the variational inequalities coming from the minimization of non-quadratic functionals. Also, we prove that the one-, two- and multi-level variants of the method in the finite element space converge, and we explicitly write the constants in the error estimations depending on the overlapping and mesh parameters. The convergence rates we find are similar with those obtained in the literature for symmetric inequalities or equations, ie. they are almost independent on these parameters in the case of the two-level and multigrid methods.

Silvia Bertoluzza, Franco Brezzi, Giancarlo Sangalli

The method of mothers for non-overlapping non-matching DDM

Location: B2 **Date:** Tuesday, July 4, 11:15 – 11:35

In the design of new domain decomposition strategies for elliptic problems it could be particularly convenient to use standard Dirichlet solvers as a brick for treating the equation in the subdomain. Indeed such solvers can easily be found already implemented and their optimization is well understood. One way of doing this is to consider as main unknown the trace ϕ of the solution of the problem: in an iterative setting, one computes at each iteration the solution u_h of the problem in each subdomain with a Dirichlet data obtained from $\phi_h(\sim \phi)$, which is then updated using a suitable approximation of the outer normal derivative of u_h. A key step is a way of uniquely determine, given ϕ_h, the value of u_h at the boundary of the subdomains. Moreover, the whole procedure needs clearly to satisfy stability and optimal accuracy. These considerations led us to define the method of mothers, which we analyse here in a version that does not require the continuity of ϕ_h on the wirebasket.

Xiao-Chuan Cai, Si Liu, Jun Zou

Fully coupled domain decomposition methods for inverse elliptic problems
Location: B1 **Date:** Wednesday, July 5, 10:50 – 11:10

Optimization problems constrained by partial differential equations have been the focus of intense research in scientific computation lately. In this presentation we propose a class of parallel full space Lagrange-Newton-Krylov-Schwarz (LNKSz) algorithms for inverse problems. In LNKSz, a Lagrangian functional is first formed according to the inverse elliptic problem and a proper regularization, and then the functional is differentiated to obtain an optimality system of nonlinear equations. Inexact Newton's method with line search is then applied directly to the fully coupled nonlinear optimality system and at each Newton's iteration the Jacobian system is solved with a Krylov subspace method preconditioned with an overlapping additive Schwarz method. We apply LNKSz to some parameter identification problems described as minimization problems constrained by elliptic partial differential equations. We report some promising results of a PETSc based parallel implementation of LNKSz for several different types of inverse elliptic problems.

Daoud Daoud

Overlapping Schwarz waveform relaxation method for the solution of the forward - backward heat equation.
Location: Bürglsaal **Date:** Tuesday, July 4, 11:40 – 12:00

In this talk we present the numerical solution of the forward-backward parabolic boundary value problem defined over $\Omega = (-1 < x < 1) \times (0,1)$ given by:

$$\begin{aligned} \sigma(x)u_t &= u_{xx} && \Omega \\ u(x,0) &= u_0(x) && 0 < x < 1 \\ u(x,1) &= u_1(x) && -1 < x < 0 \\ u(1,t) &= g_1(t) && 0 \le t \le 1 \\ u(-1,t) &= g_2(t) && 0 \le t \le 1, \end{aligned}$$

where the function $\sigma(x)$ changes sign over Ω according to the sign of x.

This type of model problem arises in various engineering applications such as boundary layer problems in fluid dynamics and steady state computation it also arises in Plasma physics and in studies of the propagation of an electron beam through the solar corona.

In 1913 and 1914 Gevrey studied this class of problem when $\sigma(x) = x^m$, where m is an odd integer. The case when $m = 1$, was studied by Baouendi and Girsvard in 1968 Goldstein and Mazumdar, and in 1984 and proved that model problems of this type are well posed in a suitably defined norm. In 1988 Vanaja considered the iterative method for solving the linear system resulting from the finite difference approximation of the forward-backward parabolic boundary value problem. Aziz and Liu transformed the second order equation into a first order system of symmetric positive definite type and solved it using a weighted least squares method. The most recent work in this area is the article by H. Han and D. Yin in 2003. Han and Yin solved the problem using a non overlapping domain decomposition method for the finite difference approximation and proved that the convergence is of order $\mathcal{O}(h)$ where h is the uniform mesh spacing for the spatial variablex. In this work we will present further iterative solution method, for the solution of the forward-backward heat equation, constructed over two overlapped subdomains, Ω^+ and Ω^-, defined in accordance to the sign of the variable x. The iterative method is set up using overlapping Schwarz wave form relaxation method to predict and correct the boundary condition at .

Victorita Dolean, Martin Gander

The relation between optimized Schwarz methods for scalar and systems of partial differential equations

Location: Bürglsaal **Date:** Tuesday, July 4, 11:15 – 11:35

Optimized Schwarz methods have been developed for scalar partial differential equations over the last decade. They achieve high performance by using transmission conditions between subdomains adapted to the physical problem solved, and are convergent even without overlap. More recently, Schwarz methods have also been extended to systems of hyperbolic equations, and it was found that even the classical Schwarz method converges without overlap in certain cases. Using the Cauchy-Riemann equations and its equivalence to associated scalar partial differential equation, we show why the classical Schwarz method converges without overlap in this case, by showing that it is equivalent to a simple optimized Schwarz method for the scalar equivalent. Using this link, we show how to develop transmission conditions with better performance than just exchanging information following the characteristics for systems of hyperbolic partial differential equations. We illustrate our findings with numerical results.

I. Charpentier[a], J.-L. Coulomb[b], Cédric Doucet[a,b,c], C. Guin[c]

On some numerical properties of the Aitken-Schwarz method

Location: B2 **Date:** Wednesday, July 5, 11:15 – 11:35

The Aitken-Schwarz domain decomposition method was first introduced by Garbey and Tromeur-Dervout in [2] for one-dimensional domain decomposition of multidimensional problems. Further developments were then dedicated to the generalization of the method on Cartesian grids [1] and on nonuniform meshes [3,4]. However, no convergence analysis was never established before. This paper is devoted to the presentation of some convergence results for the Schwarz algorithm bringing a better understanding of the method. An analytical expression of the damping factors involved in the acceleration process is deduced. We also focus on the behavior of the solutions computed in the overlapping of the subdomains. New efficient algorithms are then derived from these results.

[1] M. Garbey and D. Tromeur-Dervout, *Aitken-Schwarz Algorithm on Cartesian Grid*, 13th Int. Conf. on Domain Decomposition Methods DD13, Domain Decomposition Methods in Science and Engineering, CIMNE, Barcelona, N. Debit et Al edt, pp 53-66, 2002

[2] M. Garbey and D. Tromeur-Dervout, *Two level Domain Decomposition for Multi-clusters*, 12th Int. Conf. on Domain Decomposition Methods DD12, 2001

[3] J. Baranger, M. Garbey and F. Oudin, *Generalized Aitken-like acceleration of the Schwarz method*, Domain decomposition in science and engineering, R.Kornhuber et al editors, Lecture notes in computational science and engineering, Springer, pp 505-512, 2004

[4] A. Frullone, D. Tromeur-Dervout, *A new Formulation of Non Uniform Fourier Transform with application to Aitken-Schwarz DDM on non uniform mesh*, In Proc. Int. Conf. PCFD05, 2005

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Tino Eibner, J. M. Melenk

A multilevel solver for the boundary concentrated FEM.

Location: B1 **Date:** Tuesday, July 4, 11:15 – 11:35

The boundary concentrated finite element method is a variant of the hp-version of the finite element method that is particularly suited for the numerical treatment of elliptic boundary value problems with smooth coefficients and boundary conditions with low regularity or non-smooth geometries. For this method we present a multilevel preconditioner that leads to preconditioned stiffness matrices with condition numbers that are bounded uniformly in the problem size N. The cost the preconditioner is O(N). Numerical examples illustrate the efficiency of the algorithm.

Silvia Falletta, B. P. Lamichhane, B. I. Wohlmuth

A mortar finite element method for a heat conduction problem

Location: S2 **Date:** Wednesday, July 5, 11:15 – 11:35

We consider a heat transfer problem when a body is sliding against another body causing heat generation on the interface due to friction. Neglecting the mechanical part, we assume that the pressure on the contact interface is a known function. We consider an approach based on the Mortar technique and dual Lagrange multipliers in terms of a saddle point formulation, showing existence and uniqueness of the solution in the continuous setting. We analyze two different Finite Element Mortar formulations, providing for optimal a priori error estimates for both schemes.

Damien Tromeur-Dervout, Andrea Frullone

Non uniform discrete Fourier transform for adaptive acceleration of the Aitken-Schwarz DDM

Location: B2 **Date:** Wednesday, July 5, 11:40 – 12:00

Aitken-Schwarz DDM uses the convergence property of Schwarz DDM to accelerate the convergence of the solution at the artificial interfaces by the Aitken technique. The method uses the FFT of the traces of the solution and needs a regular discretisation of the interface. In the case of nonuniform grids, we have developed a Non Uniform Discrete Fourier Transform, based on the values of the solution at interface points. This approximation provides a framework for non conforming domain decomposition. Besides, the computation of the transfer matrix $P_{[[.,.]]}$ in the Fourier space, rather than in the physical space, provides a framework for studying the adaptivity of its approximation, based on a posteriori estimation of the Fourier modes of the error between two Schwarz iterations. The adaptivity of the approximation according to the computer architecture used and the influence of the preconditionners and solvers used have been studied.

Marc Garbey

An asynchronous parallel algorithm for the heat equation

Location: B2 **Date:** Wednesday, July 5, 10:50 – 11:10

In this paper we generalize the Aitken-like acceleration method of the additive Schwarz algorithm for elliptic problems to the additive Schwarz waveform relaxation for parabolic problems.

The main advantages of our approach are:

(1) a domain decomposition in space-time that has a high numerical efficiency.

(2) the possibility to fully exploit asynchronous message passing.

(3) a low overhead on the memory requirement, compare to traditional domain decomposition in space time.

We will discuss also the limits of the method due to the eventual non linearity of the operator, or the irregular mesh structure.

Marc Garbey, Bilel Hadri

Toward a self adaptive multi-algorithm solver for parallel CFD

Location: B2 **Date:** Friday, July 7, 10:50 – 11:10

We present a parallel elliptic solver built upon a domain decomposition technique and a subdomain solver tuning. The domain decomposition uses the framework of Schwarz algorithm however it integrates the Aitken acceleration to get the exact solution after only one iteration. This solver gathers different libraries for the resolution of a linear system such as direct method and iterative methods. Thanks to a model of prediction, given a grid size, we can evaluate with a good accuracy the elapsed time of a solver and choose the fastest solver. This solver is well designed for cluster with high latency and slow bandwidth and we will present the performances of this solver with its efficiency, its scalability. We will show comparisons with existing scientific libraries such as PETSc and SuperLU. We will illustrate our parallel solver with an implementation of an incompressible Navier Stokes flow in a pipe.

Caterina Cusulin, Luca Gerardo-Giorda

A domain decomposition procedure for the diffusion of an age-structured population in a multilayer environment

Location: S2 **Date:** Tuesday, July 4, 10:50 – 11:10

The spatial spread of a population is traditionally described by reaction-diffusion equations that model random dispersal jointly with population growth. We consider a population living in a stratified environment composed of n layers. The fertility and mortality coefficients depend on the age of individuals, while the diffusion coefficients depend on both the age and the layer. We apply a domain decomposition procedure to the original problem, by substructuring it to the global interface between the layers. We prove the convergence of the method and we give some numerical results.

Gerard Gorman, Chrisopher C. Pain, Adrian P. Umpleby, Matthew D. Piggott

Parallel anisotropic unstructured mesh optimisation for transient fluid flow problems
Location: S1 **Date:** Thursday, July 6, 10:50 – 11:10

Domain decomposition methods are instrumental in increasing the number of degrees of freedom in grid based computation to achieve a solution. The objective of adaptive mesh methods is error control – the elements of the mesh should ideally resolve the solution with a, specified, isotropic interpolation error. Equivalently, the objective is to deliver the degrees of freedom when and where they are required and to maximise computational efficiency.

Local modifications to the mesh connectivity and node position are applied iteratively to improve the overall element size and shape quality as measured in a space defined by a metric tensor field, defined here in terms of the Hessian of one or more solution fields. In parallel, the Gauss-Seidel iterative nature of the algorithm complicates the optimisation of the elements that are shared between sub-domains. A novel strategy for solving this, and the resulting load-balancing problem is presented along with performance results.

Damien Tromeur-Dervout, David Guibert

Schur DDM for stiff DAE/ODE systems for complex mechanical system 0D-modelling
Location: S2 **Date:** Thursday, July 6, 11:15 – 11:35

The large increase in 0D-modelling of complex system leads to investigate new parallel implementation of ODEs and DAEs systems. Unlike space domain decomposition, no geometrical information is given to decompose the system. The connection between unknowns have to be built to decompose the system in subsystems. A Schur Complement DDM can then be applied. The frozing of the Jacobian matrix during some time steps can be used to accelerate Krylov solvers by projecting on the Krylov subspace. This kind of DAEs are stiff and special care has to be performed during the numerical procedure.

Gundolf Haase, Manfred Liebmann

A user friendly toolbox for parallel PDE-solvers
Location: S1 **Date:** Tuesday, July 4, 10:50 – 11:10

Many implementations of parallel numerical algorithms spend a lot of time in setting up the parallel data and the communication structure. Starting from a, maybe already distributed, FE mesh we created a toolbox that automatically creates the necessary functionality to perform the communications steps in parallel algorithms based on non-overlapping elements. An extension to overlapping elements is also feasible.

The toolbox uses the C++ functionality tuned on best performance with respect to communication and to vector operations.

Bernd Heinrich

Nitsche mortaring for some elliptic problems
Location: S2 **Date:** Wednesday, July 5, 10:50 – 11:10

The paper deals with the Nitsche mortaring for treating weak continuity across non-matching meshes for some non-overlapping domain decomposition. The method is applied to different elliptic problems of second order in polygonal domains, in particular to problems with mixed boundary conditions and discontinuous coefficients as well as to singularly perturbed problems (reaction-diffusion type with parameter $\varepsilon > 0$). Due to corners on the boundary (or interface) and to small values of $\varepsilon > 0$, there are corner singularities as well as boundary layers of the solution u. In particular, the conormal derivative of $u \in H^{1+\delta}$ ($\delta > 0$) on the interface Γ does not belong to $L_2(\Gamma)$, in general. The interface Γ of the domain decomposition may coincide with the physical interface, or this interface is aligned with the boundary layer.

We apply non-matching meshes of triangles being isotropic (shape regular), anisotropic (unbounded aspect ratio for $\varepsilon > 0$) in the boundary layers, with mesh grading near the corners, or combinations of such meshes.

Some properties of the resulting non-conforming finite element schemes, the stability as well as error estimates in different norms are proved. Finally, some numerical examples are presented. The paper is based on joint work with K. Poenitz (Chemnitz).

Franck Boyer, Florence Hubert

Finite volume method for linear and non linear elliptic problems with discontinuities
Location: S1 **Date:** Wednesday, July 5, 11:40 – 12:00

Discrete Duality Finite Volume (DDFV) schemes have recently been developped to approximate monotone nonlinear diffusion problems

$$-\mathrm{div}(\varphi(z, \nabla u(z))) = f(z) \text{ in } \Omega, \quad u = 0 \text{ on } \partial\Omega,$$

on general 2D meshes. The principle of such schemes is to introduce a discrete gradient constant on a partition of the domain, called the diamonds cells to Integrate the equation on two meshes, a primal and a dual meshes. Under regularity assumptions on φ and u, we proved in *Andreianov-Boyer-Hubert 2006* that the scheme is well posed and give some error estimates.

We propose here to study the case where the domain Ω is divided into two subdomains Ω_1 and Ω_2 such that the nonlinearity φ presents some discontinuity across $\Gamma = \Omega_1|\Omega_2$. The DDFV approximation of the fluxes on the edges lying on Γ are non consistent. It is well known that in the linear isotropic case $\varphi|_{\Omega_i}(\cdot, \xi) = k_i\xi$, the consistency of the fluxes is recovered by taking the harmonic mean value of the k_i's instead of the arithmetic mean value initially given by the DDFV scheme. In this work we generalize this idea to recover the consistency of the fluxes for the general nonlinear case. We prove that our scheme is well-posed and give error estimates. We show how to solve the nonlinear scheme using a fully practical saddle-point iterative algorithm and illustrate the performance of the method.

Takashi Kako

Numerical method for wave propagation problem by FDTD method with PML
Location: Bürglsaal **Date:** Friday, July 7, 10:50 – 11:10

In this paper, we consider some mathematical and numerical problems related to Finite Difference Time Domain (FDTD) method combined with the perfectly matched layer (PML) in unbounded region. We investigate the characteristic property of PML in some detail and apply the method to 2D and 3D wave propagation phenomena by domain decomposing the original region into a bounded part and the PML region.

Vladim Korneev

Domain decomposition algorithm for discretizations of 3-d elliptic equations by spectral elements
Location: S2 **Date:** Friday, July 7, 11:15 – 11:35

The main obstacle for obtaining fast domain decomposition solvers for the spectral element discretizations of the 2-nd order elliptic equations was absence of fast solvers for the internal problems on subdomains of decomposition and their faces. It was shown by Korneev/Rytov (2005) that such solvers can be derived on the basis of the specific interrelation between the stiffness matrices of the spectral and hierarchical p reference elements. The coordinate polynomials of the latter are produced by the tensor products of the integrated Legendre's polynomials. This interrelation allows to apply to the spectral element discretizations fast solvers which in some basic features are quite similar to those developed for the discretizations by the hierarchical elements. Using these facts, we present the almost optimal in the arithmetical cost domain decomposition preconditioner-solver for the spectral element discretizations of the 2-nd order elliptic equations in 3-d domains.

Zdenek Bittnar, Jaroslav Kruis

Reinforcement-matrix interaction modelled by FETI method
Location: B2 **Date:** Tuesday, July 4, 10:50 – 11:10

Interaction between reinforcement and matrix is studied in many engineering problems, e.g. in composite analyses. Historically, the penalty method is often used but there are some difficulties with its application. Penalty parameter can lead to cancellation errors or can deteriorate condition number. This contribution deals with application of the FETI method to the problems of interaction between reinforcement and composite matrix. Continuity conditions are slightly modified and then usual tools from the FETI method are used. The FETI method can serve as a framework for perfect interaction or bonding/debonding law. Perfect interaction can be described by the classical FETI method and simple debonding laws can be solved after small modifications of the method. Simple example will show behaviour of the FETI method in such problems.

Piotr Krzyzanowski

Neumann-Neumann method for discontinuous Galerkin Stokes problem
Location: B2 **Date:** Tuesday, July 4, 11:40 – 12:00

Based on results by Pavarino and Widlund for continuous finite element discretization of the Stokes system and on recent work by Dryja and Sarkis for discontinuous Galerkin method, we develop a two level Neumann-Neumann preconditioner for the Stokes problem, discretized domain-wise with inf-sup stable elements, glued accross the subdomains using the DG approach.

Ulrich Küttler, Wolfgang A. Wall

The dilemma of domain decomposition approaches for the interaction of structures and fully enclosed incompressible fluids
Location: Bürglsaal **Date:** Wednesday, July 5, 11:40 – 12:00

Domain decomposition methods play a predominant role among solution approaches for fluid–structure interaction (FSI) problems. FSI problems occur in various areas with different properties ranging from aeroelasticity to biomechanics. Accordingly different solution techniques are required, most notably staggered schemes and iteratively coupled ones. These schemes are most commonly applied to a fluid–structure decomposition with Dirichlet–Neumann coupling. But all partitioned approaches raise a dilemma and fail in the particular case of fully Dirichlet enclosed incompressible fluids. The present contribution clearly shows this dilemma and discusses its implications on this FSI solver. An augmentation to the solver is proposed that resolves this dilemma. This augmentation involves both an additional condition on the structural solver as well as a relaxation scheme based on coupling forces. The augmented approach is presented along with some alternative approaches and its behavior is shown via some numerical examples.

Tom Lahmer, Joachim Schöberl

Homogenization techniques in sensor/actuator applications
Location: S2 **Date:** Tuesday, July 4, 12:05 – 12:25

Nowadays it is a common procedure to support the design process as well as material parameter adaption of sensors and actuators with numerical simulations.

Here, we consider sensors and actuators consisting of fine periodic structures which are repeated several hundreds of times, e.g. piezoelectric stack actuators or capacitive interdigital sensors. In order to obtain efficient algorithms, techniques of homogenization will be applied which approximate the finitely periodic structures.

The approach comprises two scales, a micro and a macroscopic one. In the microscopic scale the fine structure with periodic Dirichlet boundary conditions will be highly resolved on one exemplary micro cell. The macroscopic solution is superposed with local characteristics from the microcell, namely its eigenfunctions.

Numerical case studies for the above mentioned examples show the effect of the choice of the number of eigenfunctions on the micro cell, the order of the macro elements used, as well as the mesh size.

Sabine Le Borne

Domain-decomposition based hierarchical matrix preconditioners for the Oseen equations
Location: Bürglsaal **Date:** Wednesday, July 5, 10:50 – 11:10

Recently, hierarchical matrices have been successfully used in the construction of efficient preconditioners for scalar convection-dominated problems. In particular, a domain-decomposition approach for the index clustering in combination with an H-LU factorization has proven to lead to a robust, efficient, and parallelizable preconditioner.

In this talk, we will exploit the advantages of H-matrices to construct preconditioners for saddle point problems in fluid dynamics, in particular for the Oseen equations. We will develop several variants of preconditioners and illustrate them with numerical results.

Yvon Maday

Notion of coarse propagators in the parareal algorithm
Location: S1 **Date:** Friday, July 7, 10:50 – 11:10

The parareal in time algorithm allows for large speed up for the simulation of time dependant problem by the decomposition of the interval of propagation in time into slabs and the use of independent solution methods over each slab. This is done by choosing suitably the seed values at the beginning of each slab by through a coarse iterative method.

This algorithm allows to extend in the time direction the standard methodologies to parallel architectures that are becoming larger and larger and where the sole domain decomposition algorithms are not able to fill completely.

The efficiency of the algorithm depends on the choice of the coarse solver used in the predictor step. In this talk we shall present some ways of choosing it without degradation of the convergence performance of the algorithm but allowing for a reduction in the global CPU time.

Leszek Marcinkowski

A FETI-DP method for a mortar finite element discretization of fourth order elliptic problems
Location: S2 **Date:** Wednesday, July 5, 11:40 – 12:00

In this talk we consider a mortar discretization of a model fourth order elliptic problem in two dimensions with local HCT discretization.

The original domain is divided into polygonal subdomains, which form a geometrically conforming coarse discretization, then in each subdomain HCT finite element spaces are introduced. Using mortar technique the meshes along the interfaces are coupled, a discrete space space is introduced, and then a discrete problem is formulated.

The resulting system of linear equations is solved by a FETI-DP method. We then introduce and analyze a preconditioner which is quasi-optimal i.e. the number of CG iterations grows polylogarithmically as the sizes of the meshes decrease.

Markus Brenk, Hans-Joachim Bungartz, Miriam Mehl

Efficient implementation of domain decomposition approaches for the parallel simulation of fluid-structure-interactions
Location: S1 **Date:** Tuesday, July 4, 11:40 – 12:00

In the context of fluid-structure interactions, there are two natural starting points for domain decomposition: First, the decomposition into the fluid and the structure domain and, second, the further decomposition of those domains into subdomains for parallelisation. We describe a partitioned approach using a client-server concept for the coupling of a standalone fluid solver with a stand-alone structure solver. Our first focus is on the realisation of the coupling client which realises the complete control of the coupled simulation and provides a central triangulation of the coupling surface between the fluid and the structure domain. Our second focus is on the implementation of the fluid solver. The integrating concept is the usage of space-partitioning grids in connection with space-filling curves for both the fast and efficient link-up of coupling surface data to the spatial grids of the involved solvers and for the hardware-efficient implementation and parallelisation of the fluid solver.

Tino Eibner, Markus Melenk

H-matrix techniques for boundary concentrated FEM
Location: B1 **Date:** Tuesday, July 4, 10:50 – 11:10

It is known for elliptic problems with smooth coefficients that the solution is smooth in the interior of the domain; low regularity is only possible near the boundary. The hp-version of the FEM allows us to exploit this property if we use meshes where the element size grows porportionally to the element's distance to the boundary and the approximation order is suitably linked to the element size. In this way most degrees of freedom are concentrated near the boundary. Such meshes are particularly suited for problems with complicated boundaries and/or rough boundary conditions.

Several fast methods exists for solving the arising system of linear equations. We will discuss the use of $\mathcal{H}$-matrices. This class of matrices was introduced a few years ago by W. Hackbusch for the efficient treatment of matrices arising from the discretization of differential and integral operators. In particular, (approximate) inverses can be computed within the framework of the $\mathcal{H}$-matrix arithmetic.

In the talk we will prove that the inverse of stiffness matrices of the boundary concentrated FEM can be approximated well by $\mathcal{H}$-matrices. Numerical examples will illustrate that the $\mathcal{H}$-matrix inversion does perform well.

Martin Falcke, Chamakuri Nagaiah, Sten Rüdiger, Gerald Warnecke

Parallel numerical solution of intracellular calcium dynamics
Location: S1 **Date:** Thursday, July 6, 11:15 – 11:35

We present the parallel numerical solution of intracellular calcium dynamics. Calcium is an important second messenger in cell communication. The dynamics of intracellular calcium is determined by the liberation and uptake by cellular stores and reactions with buffers. We develop models and numerical tools to study the liberation of calcium from the endoplasmic reticulum. This process is characterized by the existence of multiple length scales. The modeling of the problem leads to a nonlinear reaction-diffusion system with natural boundary conditions in 2D. Local events, Ca2+ puffs at length scales of nanometers, originate at clusters of the inositol-1,4,5 trisphosphate (IP3) receptor channels. The interaction of these local stochastic events leads to Ca2+ waves, typically of micrometer size, which travel through the whole cell. We used the standard Galerkin method for the spatial discretization and time discretization by linearly implicit Runge-Kutta scheme. We used the CHACO package for the domain decomposition. In our description, the dynamics of IP3-controlled channels remains discrete and stochastic, and is implemented in the numerical simulation by a stochastic source term in the reaction diffusion equation. The strongly localized temporal behavior due to the on-off behavior of channels as well as their spatial localization is treated by an adaptive numerical method.

Marc Garbey, Christophe Picard

Versatile framework for solution verification of complex PDE
Location: B2 **Date:** Friday, July 7, 11:15 – 11:35

The Least Square Extrapolation (LSE) method for solution verification was introduced in 2002. SInce, the method had forked into three areas.

First, the method extends to the study of stiff elliptic problems. Techniques developed in this new framework allow to have a rigorous upper bound error estimator to predict very fine grid solutions. This work is applicable to the pressure solver in Immersed Boundary Method.

The second idea is to extend the LSE method to parabolic equations by using coarse grids solutions that have different meshes in space and time, with minimum overhead on memory.

Finally, a library was developed to compute the optimized extrapolation using the surface response methodology. Any 3D Navier-Stokes code can be plug in it to compute the optimum without knowledge of the internal structure of the code. Standard benchmark problems showed that more information can be extracted than by using Richardson Extrapolation.

P. Paule, Veronika Pillwein, J. Schöberl

Application of computer algebra tools for low energy basis functions
Location: B1 **Date:** Tuesday, July 4, 12:05 – 12:25

High order finite elements are usually defined by means of certain orthogonal polynomials. The performance of iterative solution methods depends on the condition number of the system matrix, which itself depends on the chosen basis functions.

We study overlapping Schwarz preconditioners, where we construct explicitly the decomposition of a global function into a coarse grid part and local contributions associated with the vertices, edges, faces and elements of the mesh. To make this preconditioner efficient, the basis functions should be designed such that the blocks are nearly orthogonal among each other.

First we describe the construction of basis functions minimizing the condition number, and which can be computed efficiently. In the second part we demonstrate the application of recently developed computer algebra algorithms for hypergeometric summation to derive cheap recurrence relations allowing a simple implementation for fast assemblance of the preconditioner.

Viacheslav Rabanovych

On the spectra of sums and the norms of products of orthogonal projections
Location: Bürglsaal **Date:** Tuesday, July 4, 12:05 – 12:25

The classical Schwarz alternating methods leads to the problem of estimating the spectrum bounds of the sum of orthogonal projections and the norms of their products. Consider k orthogonal projections and the identity operator I on a Hilbert space H. Assume that images Im $P_1, \ldots,$ Im P_k are linearly independent. We show that if a sum $A = P_1+P_2+\cdots+P_k$ is invertible, that is, $A \geq aI$, where $a > 0$, then

$A \leq (k-(k-1)a)I$ and the norm of a product $(I-P_1)(I-P_2)\dots(I-P_k)$ is less or equal to $(1-a)$. If in addition for some integer m, the products P_iP_j with every fixed i are nonzero only for m or less indices j, then $A \leq (m-(m-1)a))I$.

Francesca Rapetti

p-Multigrid for Fekete spectral element method

Location: B1 **Date:** Tuesday, July 4, 11:40 – 12:00

We construct and study a p-multigrid method for the solution of elliptic problems discretized with spectral elements based on Fekete nodes over simplicial meshes. A comparison with a similar method developed for classical Gauss-Lobatto spectral approches is presented. Different strategies to build up restriction and prolongation operators are analyzed: the best choice (it results that the best choice for the Fekete case is different from the Gauss-Lobatto). Numerical results point out better performances with respect to standard iterative methods.

Victorita Dolean, Frederic Nataf, Gerd Rapin

A Neumann-Neumann type algorithm for the Stokes equations using the Smith factorization

Location: Bürglsaal **Date:** Wednesday, July 5, 11:15 – 11:35

We propose a new domain decomposition method for the Stokes problem. It is derived using the Smith factorization. The key idea is the transformation of the Stokes problem into a scalar bi-harmonic problem.

We show, how a proposed domain decomposition method for the bi-harmonic problem leads to a domain decomposition method for the Stokes equations which inherits the convergence behavior of the scalar problem. Thus, it is sufficient to study the convergence of the scalar algorithm.

As transmission conditions for the resulting domain decomposition method of the Stokes problem we obtain natural boundary conditions. Therefore it can be easily implemented.

A Fourier analysis and some numerical experiments show very fast convergence of the proposed algorithm.

Marcus Sarkis

BDD and BDDC for Stabilized FEM

Location: Bürglsaal **Date:** Friday, July 7, 11:15 – 11:35

The main goal of this talk is to present new solvers based on BDD and BDDC methods for the Stokes and Dominated-Advection Diffusion Problems.

Tarek Mathew, Marcus Sarkis, Christian E. Schaerer

Block matrix preconditioners for elliptic optimal control problems

Location: B1 **Date:** Wednesday, July 5, 11:15 – 11:35

In this talk we consider block matrix algorithms for iteratively solving the saddle point linear system arising from the discretization of a linear-quadratic elliptic control problem with Neumann boundary conditions. The first algorithm we describe is based on the solution of a symmetric positive definite Schur complement system for the control variable, and employs conjugate gradient iteration. With suitable preconditioning, the rate of convergence is shown to be independent of the mesh size h, however, double iteration may be required (except in special cases). The second algorithm employs an augmented Lagrangian formulation. Preconditioners are described for the augmented saddle point system, and for a symmetric positive definite reformulation of it, both yeilding rates of convergence independent of h. Both methods avoid double iteration, and require CG or MINRES acceleration.

M. A. Ipopa, F. X. Roux, Taoufik Sassi

Generalization of Lions' nonoverlapping domain decomposition method for contact problems

Location: B1 **Date:** Friday, July 7, 10:50 – 11:10

In this talk, a generalization of Lions' nonoverlapping domain decomposition method for contact problems is proposed and studied. Ieration convergence of the continuous version of the proposed method is established. Algorithm is given and numerical results are proposed.

Simone Scacchi

Multilevel additive Schwarz and multigrid preconditioners for the bidomain system
Location: S1 **Date:** Wednesday, July 5, 11:15 – 11:35

The cardiac Bidomain model consists of a system of two degenerate parabolic reaction - diffusion equations describing the intra and extracellular potentials of the myocardial tissue. These PDEs are coupled through the reaction term with a system of ordinary differential equations, which models the ionic currents of the cellular membrane. The algebraic linear system arising from a finite element discretization in space and a semi - implicit discretization in time is ill-conditioned, and the coniugate gradient method, preconditioned by a Block Jacobi preconditioner with ILU(0) solver on each block, doesn't perform well increasing the number of subdomains. The purpose of this work is to compare the performances of Multilevel Additive Schwarz and Multigrid preconditioners, considering the number of CG iterations, the solving times and the parallel speedup, in order to find a good scalable solver for the Bidomain system. Our parallel implementation is based on the PETSc library and we run the codes on a 72 processors Linux cluster.

<u>Achim Schädle</u>, Lin Zschiedrich

Domain decomposition for Maxwell's equations: scattering off periodic structures
Location: S2 **Date:** Tuesday, July 4, 11:15 – 11:35

A domain decomposition approach for the computation of the electromagnetic field within periodic structures is presented. We use a Schwarz method with transparent boundary conditions at the interfaces of the domains. Transparent boundary conditions are approximated by the perfectly matched layer method (PML). To cope with Wood anomalies appearing in periodic structures an adaptive strategy to determine optimal PML parameters is developed. We focus on the application to typical EUV lithography line masks.

Light propagation within the multi-layer stack of the EUV mask is treated analytically. This results in a drastic reduction of the computational costs and allows for the simulation of next generation lithography masks on a standard personal computer.

C. Ross Ethier, Paul F. Fischer, <u>Khosro Shahbazi</u>

A high-order discontinuous Galerkin method for the unsteady incompressible Navier-Stokes equations
Location: B2 **Date:** Tuesday, July 4, 12:05 – 12:25

We present a high-order discontinuous Galerkin discretization of the unsteady incompressible Navier-Stokes equations in convection-dominated flows using simplicial elements. The scheme is based on a semi-explicit temporal discretization with explicit treatment of the nonlinear term and implicit treatment of the Stokes operator. The nonlinear term is discretized in divergence form by using the local Lax-Friedrichs fluxes; thus, local conservativity is inherent. Spatial discretization of the Stokes operator has employed equal-order velocity and pressure approximations. A second order approximate algebraic splitting is used to decouple the velocity and pressure calculations leading to an algebraic Helmholtz equation for each component of the velocity and a consistent Poisson equation for the pressure. The consistent Poisson operator is replaced by an equivalent operator, namely that arising from the interior penalty discretization of the standard Poisson operator. This yields a simpler and more efficient method, characterized by a compact stencil size. We demonstrate the good performance of the method by solving some popular benchmarking tests including the Orr-Sommerfeld stability problem.

Linda Stals

Discrete thin plate splines for large data sets
Location: S2 **Date:** Thursday, July 6, 10:50 – 11:10

Data fitting in high dimensions is an integral part of a number of applications including 3D reconstruction of geometric models, finger print matching, data mining, image warping, medical image analysis, and optic flow computations.

A commonly used technique to fit the data is the thin plate spline method.

Traditional thin plate splines use radial basis functions and require the solution of a dense linear system of equations whose size is proportional to the number of data points. Instead of the radial basis functions we present a method based on the use of polynomials with local support defined on finite element grids (hat functions). This method is more efficient when dealing with large data sets as the system of equations is sparse and its size depends only on the number of nodes in the finite element grid.

Theory is developed for general d-dimensional data sets and model problems are presented in 2D and 3D to study the convergence behaviour.

Matthias Maischak, Ernst Stephan

Large domain decomposition algorithms for indefinite hypersingular integral equations in three dimensions

Location: Bürglsaal **Date:** Thursday, July 6, 11:15 – 11:35

Iterative methods for linear systems of algebraic equations arising from the h- and p-version boundary element discretizations of indefinite strongly elliptic integral equations are considered. We present an additive Schwarz method which is an efficient preconditioner for the GMRES, an iterative method of conjugate gradient type. Both overlapping and non-overlapping decompositions are analyzed. Corresponding numerical results are presented. Our approach generalizes the procedures in [1] and in [2].

[1] T. Tran and E. P. Stephan, *An overlapping additive Schwarz preconditioner for boundary element approximations to the Laplace screen and Lame crack problems*, J. Numer. Math. 12 (2004), no. 4, 311-330

[2] E. P. Stephan and T. Tran, *Domain decomposition algorithms for indefinite hypersingular integral equations: the h and p versions*, SIAM J. Sci. Comput. 19 (1998), no. 4, 1139-1153

Atsushi Suzuki

A balancing Neumann-Neumann solver for Stokes problem and its application to the Earth's mantle convection problem

Location: Bürglsaal **Date:** Wednesday, July 5, 12:05 – 12:25

The Stokes equations in a spherical shell domain with slip boundary conditions plays a key role in a mathematical model of the Earth's mantle convection problem. A balancing Neumann-Neumann solver for a discretized Stokes problem by a P1/P1 finite element with a penalty type stabilization is developed. Since the stiffness matrix has a kernel that is spanneda by rigid body rotations and pressure constant, local Dirichlet solver is slightly modified. Coarse grid space is defined by local rigid body motions as usual linear elasticity problems to balance residuals for local Neumann solver. Though the Schur complement matrix with velocity and pressure unknowns is indefinite, it can be solved by the preconditioned conjugate gradient method when a break down does not occur. Our model problem for Earth's mantle convection phenomena contains two geophysical characters. One is temperature dependent viscosity with the linearized Arrhenius law and the other is the phase transition between upper and lower mantle. We will show numerical results in 3D large-scale computation.

Marcus Sarkis, Daniel Szyld

Optimal left and right additive Schwarz preconditioning of minimal residual methods with Euclidean and energy norms

Location: Bürglsaal **Date:** Tuesday, July 4, 10:50 – 11:10

For the solution of non-symmetric or indefinite linear systems arising from discretizations of elliptic problems, two-level additive Schwarz preconditioners are known to be optimal in the sense that convergence bounds for the preconditioned problem exist which are independent of the mesh and the number of subdomains. These bounds are based on some kind of *energy norm*. However, in practice iterative methods which minimize the Euclidean norm of the residual are used, despite the fact that the usual bounds are non-optimal, i.e., the quantities appearing in the bounds may depend on the mesh size; see [X.-C. Cai and J. Zou, *Numer. Linear Algebra Appl.*, 9:379–397, 2002]. In this paper, iterative methods are presented which minimize the same energy norm in which the optimal Schwarz bounds are derived, thus maintaining the Schwarz optimality. As a consequence, bounds for the Euclidean norm minimization are also derived, thus providing a theoretical justification for the practical use of Euclidean norm minimization methods preconditioned with additive Schwarz. Both left and right preconditioners are considered, and relations between them are derived. Numerical experiments illustrate the theoretical developments.

Kazufumi Ito, Jari Toivanen

Domain decomposition preconditioners for acoustic scattering in layered media
Location: S2 **Date:** Tuesday, July 4, 11:40 – 12:00

The time-harmonic acoustic scattering in layered media is modeled with an inhomogeneous Helmholtz equation for the pressure field. Examples of such problems are acoustic geological surveys and scattering littoral environments. The exterior problem is truncated into a rectangle and an absorbing boundary condition is posed on its boundaries. A low-order finite element discretization is performed on a rectangular mesh.

Subdomains which overlap only on the interfaces are defined by the domains where the material properties are constants. Each of these subdomains is embedded into a larger rectangular domains with absorbing boundary conditions. The subdomain preconditioner is a Schur complement matrix and problems with it can be solves using a fast direct solver. Based on these subdomain preconditioners a Schwarz-type preconditioner is defined. Preconditioned systems are solved using the GMRES iterations which are reduced on a neighborhood of the interfaces.

Numerical experiments demonstrate that problems with millions of unknowns can be solved in some tens of seconds in a PC. Furthermore, the convergence rate deteriorates only mildly when frequency is increased.

Yvon Maday, Julien Salomon, Gabriel Turinici

Parareal in time control for quantum systems
Location: S1 **Date:** Friday, July 7, 11:15 – 11:35

Following recent encouraging experimental results in quantum control, numerical simulations have witnessed significant improvements through the introduction of efficient optimization algorithms. Yet, the computational cost still prevents using these procedures for high-dimensional systems often present in quantum chemistry. Using the parareal in time framework, we present here a time parallelization of these schemes which allow to significantly reduce their computational cost while still finding convenient controls.

A. Ribalta, C. Stöcker, Simon Vey, A. Voigt

AMDiS - adaptive multidimensional simulations: parallel concepts
Location: S1 **Date:** Tuesday, July 4, 12:05 – 12:25

Following [Bank, Holst; SIAM Review 45 (2003) 291-323] we present a parallel approach for adaptive finite elements with reduced requirements on communication. The domain decomposition is based on equidistribution of the error on a coarse grid. Afterwards each processor is assigned to refine the coarse mesh, such that the error in its assigned domain is reduced below a given tolerance. We will discuss resudual and dual error estimates for this task. Afterwards the global solution is constructed by a partition of unity. We will introduce an efficient implementation of this scheme in the adaptive finite element toolbox AMDiS, discuss error estimates for the constructed solution and scalability of the approach, and will give an outlook towards the solution of time dependent problems.

Zoran Andjelic, Jens Breuer, Olaf Steinbach, Wolfgang L. Wendland

Fast boundary element methods for the simulation of electrical eddy current fields, their heat production and cooling
Location: Bürglsaal **Date:** Thursday, July 6, 10:50 – 11:10

One of the most challenging problems in high energy electrical devices is the simulation of the so-called hot spots and their cooling by fluid or air flow. In this lecture we present the treatment of Maxwell equations in metallic Lipschitz domains and the surrounding air by the use of an appropriate boundary integral equation formulation and a corresponding boundary element saddle-point problem in combination with domain decomposition. For the computation of the eddy current we use a Hodge decomposition on the polyhedral boundary surface involving also an inhomogeneous Laplace-Beltrami equation on the boundary surface. Once the eddy currents are computed, one has to solve a coupled nonlinear transmission problem for the temperature distribution and finally needs to couple the temperature field with a flow simulation. Under particular circumstances, the flow simulation can be replaced via Prandtl's boundary layer model which leads to a nonlinear Robin boundary condition for the temperature. Numerical results for some electrical devices such as an high energy transformer will be presented.

Xu Xuejun

Economical cascadic multigrid method (ECMG)

Location: S1 **Date:** Wednesday, July 5, 10:50 – 11:10

In this talk, an economical cascadic multigrid will be presented.Compared with the usual cascadic multigrid method,the new one requires less work operations on each level. Many computational costs can be saved in the new cascadic multigrid algorithms. Numerical experiments will be reported to support our theory.

Walter Zulehner

On Schwarz-type smoothers for saddle point problems with applications to PDE-constrained optimization problems

Location: B1 **Date:** Wednesday, July 5, 11:40 – 12:00

In this talk we consider additive (and multiplicative) Schwarz-type iterative methods as smoothers in a multigrid method for saddle point problems. Each iteration step of the Schwarz-type method requires the solution of several small local saddle point problems. In a previous work (by Joachim Schöberl and Walter Zulehner) it was shown that, under suitable conditions, the additive Schwarz-type iteration fulfills the so-called smoothing property, an important part in a multigrid convergence proof, and the theory was applied to the Stokes problem. Here we consider a certain class of optimization problems from optimal control. For the corresponding Karush-Kuhn-Tucker (KKT) conditions, a 2-by-2 block system which characterizes the solution of the optimization problems, special care is needed and some modifications are necessary in comparison with the application to the Stokes problem. The modifications are due to the fact that the $(1,1)$ block of the KKT system is positive definite only on the kernel of the $(2,1)$ block for the considered class of PDE-constrained optimization problems.

Part V

Abstracts of Posters

Menno Genseberger

Domain decomposition on different levels of the Jacobi-Davidson method

Most computational work of Jacobi-Davidson [3], an iterative method suitable for computing solutions of large eigenvalue problems, is due to a so-called correction equation on the intermediate level. In [1, 2] a strategy for the computation of (approximate) solutions of this correction equation was proposed. The strategy is based on a nonoverlapping additive Schwarz method with locally optimized coupling parameters [4, 5] in order to reduce the wall clock time and local memory requirements.

The poster presented here discusses the aspect that the domain decomposition approach can also be applied on the highest level of the Jacobi-Davidson method. Numerical experiments show that for large scale eigenvalue problems this aspect is nontrivial. Furthermore, for the combination of this domain decomposition approach and nested iterative method for eigenvalue problems, there is an elegant relation between parallel performance on distributed systems and absorbing boundary conditions at the interfaces between the subdomains.

[1] M. Genseberger, *Domain decomposition in the Jacobi-Davidson method for eigenproblems*, Ph.D. thesis, Utrecht University, The Netherlands, 2001

[2] M. Genseberger, G.L.G. Sleijpen, and H.A. van der Vorst, *An optimized Schwarz method in the Jacobi-Davidson method for eigenvalue problems*, proceedings of the 14th International Conference on Domain Decomposition Methods (DD14), Cocoyoc (Morelos) - Mexico, 2002

[3] G.L.G. Sleijpen and H.A. van der Vorst, *A Jacobi-Davidson iteration method for linear eigenvalue problems*, SIAM J. Matrix Anal. Appl., 17 (1996), pp. 401-425

[4] K.H. Tan, *Local Coupling in Domain Decomposition*, Ph.D. thesis, Utrecht University, The Netherlands, 1995

[5] K.H. Tan and M.J.A. Borsboom, *On generalized Schwarz coupling applied to advection-dominated problems*, Domain decomposition methods in scientific and engineering computing (DD7, University Park, PA, 1993), Amer. Math. Soc., Providence, RI, 1994, pp. 125-130

Moshe Israeli, Alexander Sherman

Fourier spectral solutions to variable coefficient elliptic equations

In an extension of previous work, a high order, accurate, fast, Fourier-spectral approach was developed for the Poisson, Helmholtz and "Modified Helmholtz" equations. Fourth order and Sixth order algorithms were implemented. A highly parallelizable hierarchical procedure allows an adaptive domain decomposition into small sub-domains where the solution is efficiently computed. This step is followed by a hierarchical matching to reconstruct a smooth global solution. Numerical experiments illustrate high accuracy even at coarse resolutions.

A solver for nonseparable, selfadjoint elliptic equations with variable coefficients follows by a transformation of the dependent variable via the solution of an auxiliary constant coefficient equation with optimized coefficients. There results a "Modified Helmholtz" elliptic equation with almost constant coefficients. The residual deviations from constancy are treated as inhomogeneous correction terms. A small number of iterations with the constant coefficient solver achieves convergence to very high accuracy.

Safaa J. Kasbah, Issam W. Damaj

Hardware implementation of the multigrid algorithm

Multigrid algorithms are powerful computational paradigm for solving Partial Differential Equations (PDEs) at high resolution. The computation of these solvers is complex and time consuming. Implementing Multigrid in hardware is expected to increase its computational speed and widen its use in the scientific community. In this work, we examine the feasibility of implementing the V-cycle Multigrid algorithm for the solution of 2-D Poisson equation in hardware. Field programmable hardware devices are very well adapted for the implementation of such computational intensive algorithms. The hardware performance and scalability of MG is examined using the Xilinx Virtex-II Pro Field Programmable Gate Array (FPGA). Early results demonstrate that running the V-cycle MG on an FPGA exploits the inherent parallelism of the algorithm yielding an algorithm which can outperform a software version.

Marilena Munteanu, Luca Franco Pavarino

An overlapping additive Schwarz method for monotone nonlinear parabolic problems

We study the convergence of an overlapping additive Schwarz-Richardson Algorithm for monotone nonlinear parabolic problems. Some numerical results are presented.

Philip Avery, Zdeněk Dostál, Charbel Farhat, David Horák, Vít Vondrák

Scalable FETI algorithms for frictionless contact problems

We shall present the first results of joint research concerning application of FETI based methods to the solution of 2D and 3D contact problems of elasticity. We shall briefly review basic approaches and main theoretical results concerning numerical scalability of the algorithms. The efficiency of the FETI contact algorithms will be demonstrated on the solution of 3D benchmarks.

Part VI

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