Technische Universität Graz

23. Workshop on

Fast Boundary Element Methods and Space-Time Discretization Methods

Söllerhaus, 24.–27.9.2025

U. Langer, M. Schanz, O. Steinbach, W. L. Wendland (eds.)

Berichte aus dem Institut für Angewandte Mathematik

Book of Abstracts 2025/7

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Program

Wednesday, September 24, 2025	
15.00	Coffee
16.30–16.45	Opening
16.45–17.15	R. Löscher (Graz) Paving the way to a T-coercive method for the wave equation
17.15–17.45	C. Urzúa-Torres (Delft) Space-time BEM for the wave equation in higher dimensions
17.45–18.15	M. Ospel (St. Louis) Priority-driven path expansion for acoustic Neumann scattering problems
18.30	Dinner
Thursday, September 25, 2025	
8.00–9.00	Breakfast
9.00–9.30	J. Schöberl (Wien) High order boundary element methods in NGSolve
9.30–10.00	D. Lukas (Ostrava) Polynomial operator preconditioning in 3d boundary element methods
10.00–10.30	R. Hiptmair (Zürich) Eddy current BEM based on scalar potentials without cuts?
10.30–11.00	Break
11.00–11.30	A. Boisneault (Palaiseau) Generalized optimized Schwarz method extended to FEM-BEM coupling
11.30–12.00	C. Schwarz (Bayreuth) A collocation approach of the boundary element method for linear elasticity
12.00–12.30	V. Lakshmi Keshava (Graz) Time domain BEM for elastodynamics accelerated by 3D-ACA with FMM and H-matrix techniques
12.30	Lunch
15.00	Coffee
16.00–16.30	H. Egger (Linz) Fast solvers for nonlinear time-periodic parabolic problems
16.30–17.00	C. Köthe (Graz) A space-time minimal residual method for nonlinear parabolic evolution equations
17.00–17.15	Break
17.15–17.45	H. Harbrecht (Basel) Solving acoustic scattering problems by the isogeometric boundary element method
17.45–18.15	T. Kramer (Graz) A time domain boundary element method based on the convolution quadrature method and isogeometric analysis
18.30	Dinner

Friday, September 26, 2025	
8.00–9.00	Breakfast
9.00–9.30	N. Wulbusch (Oldenburg) Numerical simulation of head-related transfer functions using fast multipole method
9.30–10.00	Z. Machaczek (Ostrava) Operator preconditioning in adaptive FEM
10.00–10.30	A. Wisse (Delft) Towards unstructured space-time finite element methods for Maxwell's equations
10.30–11.00	Break
11.00–11.30	E. P. Stephan (Hannover) Ocean circulation model for southern pacific
11.30–12.00	M. Reichelt (Graz) A space-time tensor-product finite element method for the Stokes system
12.00–12.30	T. Kaltenbacher (Graz) A simplicial space-time finite element method for the Stokes system
12.30	Lunch
13.30–18.00	Hiking Tour
18.30	Dinner
Saturday, September 27, 2025	
8.00–9.00	Breakfast
9.00–9.30	H. Gimperlein (Innsbruck) Adaptive boundary elements for wave equations
9.30–10.00	U. Langer (Linz) Goal-oriented adaptive space-time finite element methods for regularized parabolic p-Laplace problems
10.00	Closing

24. Söllerhaus Workshop on

Fast Boundary Element Methods and Space-Time Discretization Methods

24.9.–27.9.2026

Generalized Optimized Schwarz Method extended to FEM-BEM coupling

Antonin Boisneault[1,2]

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[2]Inria, Unité de Mathématiques Appliquées, ENSTA, Institut Polytechnique de Paris, Palaiseau

When solving the Helmholtz equation in a complex heterogeneous medium, it can be of interest to decompose the domain according to the variation of the wavenumber, especially when the latter is constant in some subdomains. Such problems can then be equivalently written using FEM-BEM coupling techniques, by reformulating the problems set in the homogeneous subdomains as Boundary Integral Equations. This is especially interesting for unbounded subdomains.

Recently, a Generalized Optimized Schwarz Method (GOSM) has been designed on bounded domains, with weakly imposed boundary conditions, see [1]. It differs from other OSMs by the use of a *non-local exchange operator* between subdomains, instead of the usual swap operator. This allows us to accommodate the presence of cross-points, that is, points where the interfaces of at least three subdomains intersect, which arise naturally in domain decomposition techniques.

We aim to extend this work by replacing the classical boundary conditions with interface conditions arising from several FEM-BEM coupling techniques ([2, 3]). For ease of simplicity, during the talk we restrict ourselves to only two subdomains: one heterogeneous bounded and another homogeneous unbounded. We study the well-posedness of the so-called scattering operator derived from Boundary Integral Operators, and highlight the impact of spurious resonances. Furthermore, we show that only the symmetric Costabel coupling satisfies a key assumption of the GOSM, related to the physical damping property of the system.

With this hypothesis, we prove that the GOSM applied with the Costabel FEM-BEM coupling is exponentially convergent for iterative procedures such as GMRes or Richardson. We present extensive numerical experiments to illustrate the method convergence, even for coupling techniques that do not satisfy the energy loss assumption, and discuss the impact of the choice of transmission operators on the subdomain interfaces. We illustrate the fast convergence of the method when non-local transmission operators are considered. This is joint work with Marcella Bonazzoli, Xavier Claeys, and Pierre Marchand.

References

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Eddy current BEM based on scalar potentials without cuts?

G. Brunelle, O. Stein, R. Hiptmair
Seminar für Angewandte Mathematik, ETH Zürich, Switzerland

The H-based variational formulation for the magneto-quasistatic eddy current model relies on functions in $H(\mathrm{curl}, \Omega)$ with vanishing rotation in the non-conducting region Ω_I. In Ω_I such functions can be represented by means of scalar magnetic potentials provided that the first Betti number $\beta_1(\Omega_I)$ of Ω_I vanishes, that is, Ω_I has no handles. Otherwise, the use of scalar potentials entails introducing cuts Σ, such that $\beta_1(\Omega_I \backslash \Sigma) = 0$.
Generically, the H-based boundary element formulation of the eddy current model relies on boundary integral equations (BIEs) posed on $\partial\Omega_I \cup \Omega$, though the cuts contribute only a minimal amount of information, a single scalar per connected component. We investigate modifications of those BIE, which no longer use cuts as integration domains and only require knowledge of boundaries of cuts. For Galerkin BEM this has the big benefit that we can dispense with both construction and meshing of cuts; boundaries of cuts are just closed curves and can be built and handled much more easily.

References

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Fast solvers for nonlinear time-periodic parabolic problems

Herbert Egger

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We consider a class of nonlinear time-periodic evolution problems of relevance in electrical engineering and other scientific disciplines. The existence of a unique solution is established via a fixed-point scheme and monoticity arguments. The analysis also covers the systems arising after appropriate discretization in space and time and leads to a preconditioned nonlinear iteration scheme with mesh independent contraction factors. Every step of this iteration amounts to the solution of a discrete time-periodic and time-invariant problem for which efficient parallel-in-time methods are available. The applicability and performance of the proposed method is illustrated by simulations of a power transformer involving nonlinear material laws.

Adaptive boundary elements for wave equations

Heiko Gimperlein

Engineering Mathematics, Leopold-Franzens-Universität Innsbruck, Austria

We discuss adaptive mesh refinement procedures for Galerkin and convolution quadrature discretizations of wave equations, formulated as an equivalent boundary integral equation. Reliable a posteriori error estimates of residual type are obtained for both Dirichlet and Neumann problems. The error estimates lead to adaptive boundary element methods, based on the four steps: Solve - Estimate - Mark - Refine. We present numerical experiments for space-time adaptive Galerkin elements, space adaptive and time adaptive variants, as well as extensions to convolution quadrature discretizations. The experiments confirm the theoretical results. They study the convergence and computational cost of the approaches and the reliability and efficiency of the error estimates. (joint with A. Aimi, T. Chaumont-Frelet, G. Di Credico, C. Guardasoni, I. Labarca-Figueroa and J. Nick)

Solving acoustic scattering problems by the isogeometric boundary element method

Jürgen Dölz, Helmut Harbrecht, Michael Multerer

We solve acoustic scattering problems by means of the isogeometric boundary integral equation method. In order to avoid spurious modes, we apply the combined field integral equations for either sound- hard scatterers or sound-soft scatterers. These integral equations are discretized by Galerkin's method, which especially enables the mathematically correct regular- ization of the hypersingular integral operator. In order to circumvent densely populated system matrices, we employ the isogeometric fast multipole method. The result is an algorithm that scales essentially linear in the number of boundary elements. Numerical experi- ments are performed which show the feasibility and the performance of the approach.

A simplicial space-time finite element method for the Stokes system

Tobias Kaltenbacher, Olaf Steinbach
Institut für Angewandte Mathematik, TU Graz, Austria

In this talk, we consider a space-time finite element method for the time-dependent Stokes system. While classical approaches rely on time-stepping schemes, we propose a fully space-time variational formulation in the Bochner setting. This allows for a unified treatment of spatial and temporal discretization. We further present numerical results on arbitrary and unstructured space-time meshes, which demonstrate the flexibility and effectiveness of the proposed method.

Time domain BEM for elastodynamics accelerated by 3D-ACA with FMM and H -matrix techniques

V. Lakshmi Keshava, M. Schanz

Institute of Applied Mechanics, TU Graz, Austria

The time-domain Boundary Element Method (BEM) for elastodynamics with vanishing initial conditions is considered. The spatial discretization is performed in the standard way using lower order boundary elements, while the temporal discretization is carried out with the generalized Convolution Quadrature (gCQ) method.

The gCQ framework, which extends the classical Convolution Quadrature Method (CQM), requires the evaluation of BEM system matrices of the underlying elastodynamic problem in the Laplace domain at several complex frequencies. Collecting these matrices across all sampled frequencies leads to a three-dimensional tensor structure, with one spatial matrix slice per frequency. To reduce storage and computational cost, a 3D-Adaptive Cross Approximation (3DACA) is applied to this tensor, extending the classical ACA to handle both the additional frequency dimension and the tensorial structure of elastodynamics. Within each frequency slice, the BEM matrices are further compressed using either a standard ACA algorithm using the H-matrix approach or a Chebyshev interpolation-based Fast Multipole Method (FMM). A comparative study between these two approaches is carried out.

A space-time minimal residual method for nonlinear parabolic evolution equations

Christian Köthe, Olaf Steinbach
Institut für Angewandte Mathematik, TU Graz, Austria

Nonlinear parabolic problems arise in many applications, such as e.g., electric machine simulation when considering the eddy current approximation of the Maxwell system. In this talk we combine a minimal residual method together with a fully unstructured space-time discretization scheme for the solution of nonlinear parabolic evolution equations. The nonlinear minimization problem will be solved using a Gauß-Newton scheme and the built-in error estimator of the minimal residual method will be used to drive an adaptive refinement scheme in space and time. Numerical examples demonstrate the correctness of the proposed approach.

A time domain boundary element method based on the convolution quadrature method and isogeometric analysis

Thomas Kramer, Benjamin Marussig, Martin Schanz
Institute of Applied Mechanics, TU Graz, Austria

Scattering problems in an isotropic homogeneous medium, such as the propagation of a pressure wave in acoustics and linear elastic waves in elastodynamics, are modeled here with an isogeometric boundary element method. The boundary element method (BEM) facilitates wave radiation simulations in infinite exterior domains by reducing the problem to the scatterer's surface. This motivates an exact parametrization of the possibly curved manifold by connected spline patches. The unknown Cauchy data on this manifold are the solutions to boundary integral equations based on time-dependent convolution integrals. Using the convolution quadrature method (CQM), an approximate solution in the time domain is held by a quadrature rule with quadrature weights based on the solution to discretized elliptic problems in the Laplace domain [1]. Continuous and discontinuous B-spline basis functions span the approximative solution space to those discretized elliptic problems. Combining a multi-stage Runge-Kutta-based CQM with the spline approximations in the spatial variable enables an over all higher-order method in space and time. We measure the approximation quality by investigating the convergence rate in a combined space and time error norm based on uniform refinement in both variables. Applied is the direct Galerkin BEM with mixed boundary conditions [2]. Numerical experiments demonstrate the higher-order capability of the overall method. Implementational aspects are given, explaining the incorporation of IGA into existing integration routines using order elevation [3] and Bézier extraction [4].

References

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Goal-oriented adaptive space-time finite element methods for regularized parabolic p-Laplace problems

Bernhard Endtmayer[1], Ulrich Langer[2], Andreas Schafelner[2]

[1]Institut für Angewandte Mathematik, Leibniz Universität Hannover, Germany
[2]Institut für Numerische Mathematik, Johannes Kepler Universität Linz, Austria

We consider goal-oriented adaptive space-time finite-element discretizations of the regularized parabolic p-Laplace problem on completely unstructured simplicial space-time meshes. The adaptivity is driven by the dual-weighted residual (DWR) method since we are interested in an accurate computation of some possibly nonlinear functionals at the solution. Such functionals represent goals in which engineers are often more interested than the solution itself. The DWR method requires the numerical solution of a linear adjoint problem that provides the sensitivities for the mesh refinement. This can be done by means of the same full space-time finite element discretization as used for the primal non-linear problems. The numerical experiments presented demonstrate that this goal-oriented, full space-time finite element solver efficiently provides accurate numerical results for different functionals.

References

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Paving the way to a T-coercive method for the wave equation

Richard Löscher
Institut für Angewandte Mathematik, TU Graz, Austria

In this talk we take a first step toward introducing a space-time transformation operator T that establishes T-coercivity for the weak variational formulation of the wave equation in space and time on bounded Lipschitz domains. As a model problem, we study the ordinary differential equation (ODE) $u''+\mu u = f$ for $\mu > 0$, which is linked to the wave equation via a Fourier expansion in space. For its weak formulation, we introduce a transformation operator T_μ that establishes T_μ-coercivity of the bilinear form yielding an unconditionally stable Galerkin-Bubnov formulation with error estimates independent of μ. The novelty of the current approach is the explicit dependence of the transformation on μ which, when extended to the framework of partial differential equations, yields an operator acting in both time and space. We pay particular attention to keeping the trial space as a standard Sobolev space, simplifying the error analysis, while only the test space is modified. The theoretical results are complemented by numerical examples.

Polynomial operator preconditioning in 3d boundary element methods

Dalibor Lukáš, Zbyšek Machaczek
Department of Applied Mathematics, VSB TU Ostrava, Czech Republic

In operator preconditioning we utilize the opposite-order mapping properties of the single-layer and hyper-singular boundary integral operators. However, in 3 spatial dimensions the lowest-order discretizations of the operators by discontinous piecewise constant and continuous piecewise linear functions, respectively, do not match in terms of degrees of freedom. Therefore, a dual mesh is often introduced to discretize the single-layer operator. Unfortunately, the assembly of the preconditioner is significantly more expensive than the operator itself. In this talk we analyze a recently introduced construction of continuous piecewise cubic basis functions to discretize the hyper-singular operator in 3d. This time we present a proof that it forms an optimal preconditioner to the original single-layer operator discretized by the piecewise constants. We give numerical experiments implemented on a GPU to document that the performance of our method is significantly better than the standard dual-mesh preconditioner.

Operator Preconditioning in Adaptive FEM

Zbyšek Machaczek

Department of Applied Mathematics, VSB TU Ostrava, Czech Republic

In this talk, we discuss the construction of opposite order preconditioners for the finite element stiffness matrix using a Galerkin discretization of the Newton potential. Since the Newton potential only provides a particular solution, appropriate mapping properties must be enforced using further potentials. We will describe the computation of near field matrix coefficients using Duffy regularization for pairs of tetrahedrons, where optimized simplex quadrature rules are utilized. Finally, numerical experiments on 2D and 3D locally refined meshes will be presented.

Priority-driven path expansion for acoustic Neumann scattering problems

Matthias Ospel
ISL, St. Louis, France

We introduce an iterative path expansion scheme for acoustic wave scattering that treats propagation as a priority driven local search, eliminating the dense operator assembly required by classical boundary element methods. Starting from the Kirchhoff-Helmholtz equation, we employ Rubinowicz's derivation to establish the theoretical bridge to edge diffraction integrals and model the solution of inhomogeneous boundary value problems as a superposition of discrete propagation paths. A binary max heap manages computations of reflections and diffractions by equivalent source strength, targeting the most influential path segments. The resulting iterative forward-stepping algorithm captures arbitrarily deeply nested scattering without global matrix operations, yielding a cost that scales with the number of dynamically selected paths rather than surface discretization; the algorithm is also trivially parallelizable. Scattering benchmarks show that the method converges rapidly and yields relative L^2-norm differences $< 5\%$ of direct boundary element formulations across multiple wavenumbers.

A space-time tensor-product finite element method for the Stokes system

Richard Löscher, Michael Reichelt, Olaf Steinbach
Institut für Angewandte Mathematik, TU Graz, Austria

In this talk, we consider the time-dependent Stokes system in a space-time setting. While the stationary Stokes system yields a symmetric saddle point system, we demonstrate that in a space-time setting this is not the case. However, one can still achieve a system with off diagonal blocks being adjoint to one another by considering the velocity as well as the pressure in anisotropic Sobolev spaces. The presentation will comprise theoretical considerations as well as numerical results. The occurring finite element matrices of the anisotropic setting are realized using a modified Hilbert transform.

High Order Boundary Element Methods in NGSolve

Rafael Dorigo, Joachim Schöberl, Lucy Weggler

We present a recent open source implementation of high order boundary element methods within the finite element package NGSolve. It supports the evaluation of potential operators and boundary integral operators. Operators can be combined with flexible Python scripting. Near field integrals are evaluated using Sauter Schwab integration rules, compression is obtained by the fast multipole method. Multipole operations are performed using stable recurrence relations with orders above 1000.
A tutorial is available from: https://weggler.github.io/ngbem/intro.htm

A collocation approach of the boundary element method for linear elasticity

Christina Schwarz
Chair of Scientific Computing, University of Bayreuth, Germany

Solving mixed boundary value problems by the boundary element method generally leads to non-sparse matrices. To reduce memory requirements, we approximate the involved operators using hierarchical matrices [1]. Furthermore, to accelerate simulations we aim to replace the Galerkin method by collocation for the discretisation of the operators.
However, the standard formulation of the boundary integral equations involves a hypersingular integral operator, which is not well-defined in the context of collocation. In order to avoid this operator, we use a mixed approximation technique which was introduced by Olaf Steinbach for the Laplace equation [2]. To ensure stability, two nested grids are required for the discretization of the integral operators.
Finally, the collocation approach – enhanced with some additional optimisations – is applied to the Lamé equation from linear elasticity to significantly speed up the simulation process.

References

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Ocean Circulation Model for Southern Pacific

Ernst P. Stephan
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We consider the primitive equations of the ocean circulation model for the southern pacific, which consists of the time-dependent Navier-Stokes equations in the β-plane coupled with the temperature transport equation. The El Niño phenomenon is simulated by the action of given wind stresses on the ocean surface. We present an approximation scheme with Crank-Nicolson finite differences in time, and in space we take inf-sup stable Galerkin finite elements for the Navier-Stokes part and bilinear elements for the temperature. We solve the resulting, nonlinear monolithic discrete system by Newton´s method. Numerical experiments are given which show the practicability of our approach.

Space-time BEM for the wave equation in higher dimensions

Daniel Hoonhout, Carolina Urzúa-Torres

Delft Institute of Applied Mathematics, Delft University of Technology, Netherlands

In this talk, we consider stable space-time boundary element methods (BEM) for transient wave problems with prescribed Dirichlet data and zero initial conditions when the spatial domain has dimension larger than 1. For this, we use the formulations proposed in [1], for which the related boundary integral equations have continuity and inf-sup conditions in trace spaces of the same regularity. Moreover, we present the numerical results of a standard low-order space-time implementation with two spatial dimensions and highlight the similarities and differences between the 1d and the higher dimensional cases.

References

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Toward unstructured space-time finite element methods for Maxwell's equations

Carolina Urzúa-Torres, Anouk Wisse

Delft Institute of Applied Mathematics, Delft University of Technology, Netherlands

In this preliminary work, we take first steps toward developing unstructured space–time finite element methods for Maxwell's equations. By rewriting Maxwell's equations as a vectorial wave equation, we build on the theoretical framework established in [1], where existence and uniqueness were proven for this formulation under the Weyl gauge with right hand side in L^2. This formulation naturally supports the use of tensor-product bases in a finite element context. Exploiting structural similarities between the vectorial and scalar wave equation, we show additional properties of the vectorial wave equation, taking inspiration from the theory in [2]. Finally, we will discuss our next steps on how to extend the theory to more general settings.

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Numerical simulation of head-related transfer functions using fast multipole method

Nick Wulbusch

Institut für Mathematik, Carl von Ossietzky Universität Oldenburg, Germany

In this talk, we present an overview of simulating head-related transfer functions (HRTFs) using the Mesh2HRTF software, a widely used tool in the hearing acoustics community. The software employs a collocation boundary element method (BEM) combined with the multi-level fast multipole method (MLFMM) for efficient acoustic simulations. We introduce the Burton-Miller formulation of the underlying acoustic problem and describe the fast multipole method implemented in this framework. Typical surface meshes and simulation results will be shown to illustrate the workflow. Finally, we discuss practical challenges and highlight potential areas for improvement, such as adaptive FMM techniques.

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