

**A journey in numerical linear
algebra: a workshop in honor
of Michele Benzi's 60th
birthday**

Report of Contributions

Contribution ID: 1

Type: **not specified**

Augmented Lagrangian preconditioner for fluids on surfaces

Saturday, 11 June 2022 11:15 (30 minutes)

Augmented Lagrangian preconditioner for linearized incompressible Navier-Stokes equations has been introduced in [1,2]. Over the years it was proved to be an efficient technique to solve highly non-symmetric algebraic systems having a saddle point structure and resulting from discretizations of fluid problems. In the talk we review the approach and discuss some of its recent developments. In particular, we introduce the Augmented Lagrangian preconditioner for the algebraic systems of unfitted finite element discretizations of fluid equations posed on smooth closed surfaces. A matrix of the system features a sign-indefinite (2,2)-diagonal block with a high-dimensional kernel that requires special handling. We further consider a reuse of matrix factorization as a building block in the full and modified Augmented Lagrangian preconditioners. The strategy, applied to solve two-dimensional incompressible fluid problems, yields efficiency rates independent of the Reynolds number. The talk partially covers results from [3].

References

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- [3] M. Olshanskii and A. Zhiliakov, Recycling augmented Lagrangian preconditioner in an incompressible fluid solver, *Numerical Linear Algebra with Applications* 29 (2022), e2415.

Presenter: OLSHANSKII, Maxim (Department of Mathematics, University of Houston)

Contribution ID: 2

Type: **not specified**

Differential-algebraic systems with symmetry structures

Saturday, 11 June 2022 08:45 (30 minutes)

Linear time-varying differential-algebraic equations with extra symmetries such as self-adjoint and skew-adjoint systems are studied. Local and global canonical forms under congruence are presented and used to classify the geometric properties of the flow associated with the differential equation as symplectic or generalized orthogonal flow. As applications, the results are applied to the analysis of dissipative Hamiltonian systems arising from circuit simulation and incompressible flow.

Joint work with Peter Kunkel.

Presenter: MEHRMANN, Volker (TU Berlin)

Contribution ID: 3

Type: **not specified**

On non-Hermitian positive (semi)definite linear algebraic systems arising from dHDAE systems

Saturday, 11 June 2022 09:15 (30 minutes)

It is well known that every matrix $A \in \mathbb{C}^{n \times n}$ can be split into its Hermitian and skew-Hermitian parts, i.e.,

$A = H + S$, $H = \frac{1}{2}(A + A^*)$, $S = \frac{1}{2}(A - A^*)$, so that $H = H^*$ and $S = -S^*$. This simple, yet fundamental observation = $H + S$ lies in or on the smallest rectangle with sides parallel to the real and imaginary axes that contains all eigenvalues of Hermitian matrices A are sometimes called positive real or positive stable, but we call $A = H + S$ positive (semi)definite.

In the first part of this talk we will discuss an important class of practically relevant applications where the splitting $A = H + S$ occurs naturally and has a physical meaning. These applications arise from based modeling using differential algebraic equation (DAE) systems in dissipative Hamiltonian (dH) form.

In the second part we will study the linear algebraic systems arising in this context, and their solution by Krylov subspace methods. The (non-Hermitian) matrices A that occur are positive definite or positive semidefinite. In the positive definite case we can solve the linear algebraic systems using Krylov subspace methods based on efficient three-term recurrences. Such methods were already derived by Widlund [6] (based on earlier work of Concus and Golub [3]) and Rapoport [5]

in the late 1970s. These methods are not widely used or known, and we will therefore summarize the most important facts about their implementation and their mathematical properties. The semidefinite case can be challenging and requires additional techniques to identify and deal with

the “singular part” of the matrix, while the “positive definite part” can still be treated with the three-term recurrence methods. We will illustrate the performance of the iterative methods and compare them with (preconditioned) GMRES on several computed examples.

The talk is based on joint work with Candan Gdc, Volker Mehrmann, and Daniel B. Szyld [4].

References

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Numer. Anal., 15 (1978), pp. 801–812.

Presenter: LIESEN, Jörg (TU Berlin)

Contribution ID: 4

Type: **not specified**

Provable convergence rate for asynchronous methods via randomized linear algebra

Saturday, 11 June 2022 09:45 (30 minutes)

Asynchronous methods refer to parallel iterative procedures where each process performs its task without waiting for other processes to be completed, i.e., with whatever information it has locally available and with no synchronizations with other processes. For the numerical solution of a general partial differential equation on a domain, Schwarz iterative methods use a decomposition of the domain into two or more (usually overlapping) subdomains. In essence one is introducing new artificial boundary conditions. Thus each process corresponds to a local solve with boundary conditions from the values in the neighboring subdomains.

Using this method as a solver, avoids the pitfall of synchronization required by the inner products in Krylov subspace methods. A scalable method results with either optimized Schwarz or when a coarse grid is added. Numerical results are presented on large three-dimensional problems illustrating the efficiency of asynchronous parallel implementations.

Most theorems show convergence of the asynchronous methods, but not a rate of convergence. In this talk, using the concepts of randomized linear algebra, we present provable convergence rate for the methods for a class of nonsymmetric linear systems. A key element in the new results is the choice of norm for which we can prove convergence of the residual in the expected value sense.

Presenter: SZYLD, Daniel (Temple University)

Contribution ID: 5

Type: **not specified**

Null space-based approaches for the least squares and symmetric saddle-point problems

Friday, 10 June 2022 15:30 (30 minutes)

Consider saddle-point systems of the following form

$$A \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} A & B^T \\ B & 0 \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = \begin{pmatrix} f \\ g \end{pmatrix} \quad (1) \text{ where } A$$

$\in \mathbb{R}^{n \times n}$ is large, sparse and symmetric positive definite and $B \in \mathbb{R}^{k \times n}$ ($n > k$) has full rank. Such systems arise in various scientific applications, including the finite element approximation of PDEs in which a constraint is enforced on a subset of unknowns via a global scalar Lagrange multiplier, numerical continuation methods for large nonlinear systems of equations, constrained optimization as well as in linear least squares problems [2].

Null-space methods represent one of possible solution approaches to solve such systems. Despite these solution approaches that compute a null-space $Z \in \mathbb{R}^{n \times (n-k)}$ basis of the undetermined block B are traditional in various engineering communities and offer advantages in some situations, general techniques to obtain such bases useful for large and sparse A have not been studied frequently in the past. There are more reasons for this. One of them may be that the resulting transformed system with the matrix $Z^T A Z$ is often dense, or ill-conditioned, or both. Another reason may be that there is a lack of efficient preconditioners for the transformed systems even when the projected matrix $Z^T A Z$ is reasonably sparse. The core of the talk is devoted to discussing various algorithms to find the null-space basis Z . Although in several of the approaches treatment of B that does not have full-rank is not difficult, we do not treat such cases at length.

Initial motivation for studying the null-space approaches in this talk is slightly different from the symmetric saddle-point problem given above. Consider the linear least-squares (LS) problem $\min_x \|Ax - b\|_2$, where the system matrix $A \in \mathbb{R}^{m \times n}$ ($m \geq n$) and the right-hand side $b \in \mathbb{R}^m$ are given. Assume that a part of the rows of A is dense and the rows have been initially permuted such that the dense rows are the last rows of A . If we assume a conformal partitioning of the vector b we have $A = \begin{pmatrix} A_s \\ A_d \end{pmatrix}$, $A_s \in \mathbb{R}^{m_s \times n}$, $A_d \in \mathbb{R}^{m_d \times n}$, $b = \begin{pmatrix} b_s \\ b_d \end{pmatrix}$, $b_s \in \mathbb{R}^{m_s}$, $b_d \in \mathbb{R}^{m_d}$, where m_s denotes the number of sparse rows of A , and m_d is the number of dense rows, with $m = m_s + m_d$, $m_s \geq n > m_d \geq 1$ and $m_d \ll m_s$.

The normal equations that describe the solution [3] (not representing always the best way to get the solution) become

$$A_s^T b_s + A_d^T b_d, \quad Cx = (C_s + A_d^T A_d)x = c, \quad c = A_s^T b_s + A_d^T b_d, \quad (2) \text{ where } C_s = A_s^T A_s \text{ is the reduced normal matrix.}$$

The solution of (2) can be obtained from the equivalent $(n + m_d) \times (n + m_d)$ system

$$\begin{pmatrix} C_s & A_d^T \\ A_d & -I \end{pmatrix} \begin{pmatrix} x \\ A_d x \end{pmatrix} = \begin{pmatrix} c \\ 0 \end{pmatrix} \quad (3) \text{ This is the system nearly of the form}$$

$= m_d$, $H = C_s$, $B = A_d$. But the $(2, 2)$ block is nonzero and equal to the negative unit matrix of the appropriate dimension. Provided A_s has full column rank, C_s is symmetric positive definite. But the null-space based approach can be extended even if the $(2, 2)$ block is nonzero and C_s only positive semidefinite. This positive definiteness is quite common in the LS problems even when the whole A is of full column rank. The approach to solve (3) also in this case for the full rank LS problem (3) is motivated by the following simple lemma.

Lemma: Consider $A = A_s A_d$, $A_s \in \mathbb{R}^{m_s \times n}$, $A_d \in \mathbb{R}^{m_d \times n}$. If A is of full column rank, then $C_s = A_s^T A_s$ is positive definite on the null space of A_d .

Success of any null-space approach then depends on constructing a suitable null-space basis that keeps the matrix $Z^T A Z$ sufficiently sparse and well-conditioned. Of course, it cannot be an orthogonal null-space basis computed, for example, by pivoted QR factorization of B^T . We will

discuss other approaches to find the null-space basis heavily based on the fact that B is wide. That is, it has far fewer rows than columns. The approaches include computing an oblique basis Z computed from more separate QR factorizations and an approach that adds rows of B one by one and extends the basis incrementally. Another approach for constructing Z is the right oblique conjugation. Applied to $B \in \mathbb{R}^{k \times n}$ it yields $V \in \mathbb{R}^{n \times n}$ and lower trapezoidal $L \in \mathbb{R}^{k \times n}$ satisfying $BV = L$. (4) The null-space basis is then formed by the last $n - k$ columns of V . This approach is directly related to Thesis of Michele Benzi [1]. Techniques implied by this Thesis have motivated the right oblique conjugation, and they may still offer further computational possibilities. Not only for constructing Z but possibly also for preconditioning of the linear systems with the matrix $Z^T AZ$.

Our experimental results show that the null-space bases obtained from the mentioned approaches are of high quality and can push forward further research in optimization and solving constrained least squares. Linear least squares problems that contain a small number of dense rows arising from practical applications are used to illustrate our ideas and to explore their potential for solving large-scale systems. Our work was originally motivated by the paper by Howell [4]. A significant part of the obtained results has been published in [5].

References

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Presenter: TŮMA, Miroslav (Charles University)

Contribution ID: 6

Type: **not specified**

What makes a network "complex"?

Friday, 10 June 2022 15:00 (30 minutes)

The advent of Network Science was precipitated by an urgent need to decipher simple mechanisms that could explain the formation and growth of natural and man-made networks. The large-scale structural patterns of these networks systematically deviate from stylized models such as random networks or lattices in a variety of ways, which include the existence of phenomena like "small-worldness"(SW) and "scale-freeness"(SF) (see [1] and refs. therein).

Although these mechanisms explain some of the structural properties of real-world networks they also open intriguing questions. For instance, it is easy to see that the SW mechanism reduces mean path length simply by creating shortcuts, making enhanced connectivity overly dependent –and thus, fragile–on them. Likewise, SF-like networks are robust against random node removal but highly fragile against selected removal of highly connected nodes (hubs). It turns out that an optimal (geodesic) navigation of SW and SF networks tends on average to "overuse" both shortcuts or hubs, making these the first candidates to experience jamming, a property that induces a failure cascade which can severely harm the macroscopic network's function.

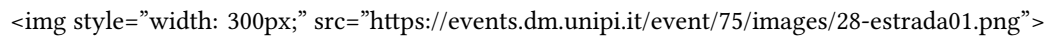
Here we investigate the microscopic structure of SW and SF networks and discovered that both mechanisms generate topological bypasses connecting pairs of nodes, which facilitates the network communication beyond the topological shortest paths. We model the dynamics on the network by using the time-dependent Schrodinger equation with a tight-binding (TB) Hamiltonian H . Then, the real-time propagator $e^{-itH/\hbar}$ is mapped into the thermal propagator $e^{-\beta H}$, where β is the inverse temperature of a thermal bath in which the network is submerged to. After setting appropriately the TB parameters we get that $\mathcal{H} = -A$, such that we define:

$\xi_{vw}(\beta) := \langle \psi_v - \psi_w | e^{\beta A} | \psi_v - \psi_w \rangle$, (1) which accounts for the $\langle i >$ resistance $\langle i >$ offered by the network to the displacement of the particle from the node v to the node w in inverse set.
We proved that $\xi_{vw}(\beta)$ is a square Euclidean distance between the pair of nodes v and w [2].

Further we define a walk-based network entropy, which accounts for the structural ordering of the network produced by the emergence of walks among pairs of nodes. Using it, we shown that both mechanisms, SW and SF, increase network entropy as a result of rocketting the choices that the particle has to navigate between every pair of nodes (see Fig. 1). Therefore, a particle navigating between a pair of nodes v and w can go through the topological shortest path (SP) connecting it or via some of the alternative bypasses created by the SW and SF mechanisms. We assume that the particle will "select" such a path that minimizes the thermal resistance between the two nodes. Based on $\xi_{vw}(\beta)$ we obtain the energy ϵ that a particle needs to travel between a given pair of nodes using a given path that connects them. The path for which the particle needs minimum energy among all which connect a pair of nodes is named the thermally resistive shortest paths (TRSP).

We investigate when the TRSP is favored over the SP for the navigation between pairs of nodes in a network created by the Watt-Strogatz (WS) SW mechanism as well as by the Barabasi-Albert (BA) SF one. The results are illustrated in Fig. 1. We can see that the change of the net energy factor ϵ exhibits a non-monotonic shape as a function of the rewiring probability p in the so-called small-world regime. In fact, our measure detects a minimum for $p \approx 0.15$ at which, on average, traveling through the TRSP is energetically much more favorable than traveling through the SP. We call this probability the "good navigational point"(GNP) of the network, $pGNP$. This is also observed in panel (b) for the BA model. Observe that ϵ is again non-monotonic with a minimum close to $\langle k \rangle \approx 11$, i.e. BA model for which $\langle k \rangle_{GNP} \approx 11$. Finally, we show how this property influences dynamical processes (synchronization and diffusion) taken place on the networks and investigate the existence of such bypasses in several real-world networks. Therefore we conclude that:

"a network is complex when its structure is sufficiently rich in walks connecting pairs of nodes as for TRSP emerge as alternative routes that avoid SP and through-hubs navigation, which therefore increases network robustness against jamming".



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Presenter: ESTRADA, Ernesto (Institute of Cross/Disciplinary Physics and Complex Systems, UIB-C-SIC, Palma de Mallorca)

Contribution ID: 7

Type: **not specified**

Computing the Square Root of a Low-Rank Perturbation of the Scaled Identity Matrix

Friday, 10 June 2022 17:00 (30 minutes)

We consider the problem of computing the square root of a perturbation of the scaled identity matrix, $A = \alpha I_n + UV^*$, where U and V are $n \times k$ matrices with $k \leq n$.

This problem arises in various applications, including computer vision and optimization methods for machine learning. We derive a new formula for the p th root of A that involves a weighted sum of powers of the p th root of the $k \times k$ matrix $\alpha I_k + V^*U$. This formula is particularly attractive for the square root, since the sum has just one term when $p = 2$. We also derive a new class of Newton iterations for computing the square root that exploit the low-rank structure. We test these new methods on random matrices and on positive definite matrices arising in applications. Numerical experiments show that the new approaches can yield much smaller residual than existing alternatives and can be significantly faster when the perturbation UV^* has low rank.

This is joint work with Massimiliano Fasi and Xiaobo Liu.

Presenter: HIGHAM, Nick (University of Manchester)

Contribution ID: 8

Type: **not specified**

Improved parallel-in-time integration via low-rank updates and interpolation

Saturday, 11 June 2022 10:15 (30 minutes)

This talk is concerned with linear matrix equations that arise from the space-time discretization of time-dependent linear partial differential equations (PDEs). Such matrix equations have been considered, for example, in the context of parallel-in-time integration leading to a class of algorithms called ParaDiag, see [1] and the references therein. In this talk, we describe and analyze two novel approaches for the numerical solution of such equations. Our first approach is based on the observation that the modification of these equations performed by ParaDiag in order to solve them in parallel has low rank. Building upon previous work on low-rank updates of matrix equations [2], this allows us to make use of tensorized Krylov subspace methods or the techniques from [4] to account for the modification. Our second approach is based on interpolating the solution of the matrix equation from the solutions of several modifications. Both approaches avoid the use of iterative refinement needed by ParaDiag and related space-time approaches [3] in order to attain good accuracy. In turn, our new approaches have the potential to outperform, sometimes significantly, existing approaches. This potential is demonstrated for several different types of PDEs.

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Presenter: KRESSNER, Daniel (EPFL)

Contribution ID: 9

Type: **not specified**

Computing the most stable switching laws of a linear system.

Saturday, 11 June 2022 11:45 (30 minutes)

When considering the stability under arbitrary switching of a discrete-time linear switched system $x(n+1) = A_{\sigma(n)}x(n)$, $\sigma : \mathbb{N} \rightarrow \{1, \dots, m\}$, where $x(0) \in \mathbb{R}^d$, the matrix $A_{\sigma(n)} \in \mathbb{R}^{d \times d}$ belongs to a finite family $F = \{A_i\}_{1 \leq i \leq m}$ and σ denotes the switching law, it is called *spectrum-minimizing product* of the family F . The minimal rate of growth of its trajectories is called *lower spectral radius* $\rho(F)$. For a normalized family F of matrices (i.e., with lower spectral radius $\hat{\rho}(F) = 1$) that share an invariant cone [1, 2] and show how to generalize some of the known results to this more general setting (Guglielmi & Zennaro, in progress [5]). These generalizations are of interest because common invariant multicones may well exist when common invariant cones do not.

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Presenter: GUGLIELMI, Nicola (Gran Sasso Science Institute)

Contribution ID: 10

Type: **not specified**

Reduced-Order Models for Parametrized PDE Models with Constraints

Friday, 10 June 2022 17:30 (30 minutes)

Various phenomena simulated using partial differential equations (PDEs) give rise to constrained systems of equations. These include models of optimal control with constraints given by elliptic PDEs, as well as fundamental models of fluid dynamics such as the Stokes equations where the constraints correspond to the incompressibility (divergence-free) condition. If these models also depend on random (parametrized) input data, then it is important to develop reduced-order models (ROMs) to reduce the computational costs associated with multiple solutions of the large-scale algebraic systems that arise from discretization. Several approaches have been developed to construct ROMs for constrained problems. These approaches supplement greedy search strategies [4] with methods that augment the spaces obtained from searching in order to enforce inf-sup stability, which otherwise does not hold in the reduced spaces. In this work, we present two sets of results. The first is a comparison of the effectiveness of two such methods for augmentation, known as aggregation methods [3] and supremizing methods [1, 2]. The second is an introduction of a new approach that avoids the difficulties caused by lack of inf-sup stability by forcing the reduced model to have a simpler structure not of saddle-point form.

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Presenter: ELMAN, Howard (University of Maryland at College Park)

Contribution ID: 11

Type: **not specified**

Rational Krylov subspaces for Hermitian matrices: properties and applications

Friday, 10 June 2022 16:00 (30 minutes)

Rational Krylov subspaces have become a fundamental ingredient in numerical linear algebra methods associated with reduction strategies. Nonetheless, a lot of their potential is still to be explored.

In particular, many structural properties of the reduced matrices in these subspaces are not fully understood. We advance in this analysis by deriving decay bounds on the entries of rational Krylov reduced matrices and of their functions, which hold in spite of the lack of any banded structure in the considered matrices.

Moreover, when data matrices are Hermitian, a short-term recurrence can be used to generate an associated orthonormal basis. We propose an implementation that allows one to obtain the rational subspace reduced matrices at lower overall computational costs than proposed in the literature. Applications are discussed where the short-term recurrence feature can be exploited to avoid storing the whole orthonormal basis.

This presentation is based on joint works with Davide Palitta, Università di Bologna, and Stefano Pozza, Charles University, Prague.

Presenter: SIMONCINI, Valeria (Università di Bologna)

Contribution ID: 12

Type: **not specified**

Towards Resilient and Robust Asynchronous Linear Systems Solvers for Edge Computing

Friday, 10 June 2022 18:00 (30 minutes)

Wearable healthcare devices, content delivery systems, and smart home devices are pushing applications, data, services and, consequently, large-scale computations away from centralized environments onto the network, closer to the requests. Newly emerging technology of *edge computing*, where networked, autonomous devices work collaboratively to achieve a common goal through the synergy of humans and machines, requires asynchronous, flexible and resilient algorithms for decentralized processing, communication and predictions in heterogeneous environments. While the benefits of developing autonomous capabilities are multifold, edge computing systems are subject to device failures, partial data losses, or security attacks, and hence require multidimensional resilience solutions. In this talk, we will present our recently developed resilience and robustness improvements when solving linear systems of equations with asynchronous Jacobi (ASJ) method. Inspired by the ADMM (Alternating Direction Method of Multipliers) and average consensus push-sum, we derived rejection and update criteria that allow to restore the convergence of the original ASJ method in the presence of data corruption or communication delays.

Presenter: MIEDLAR, Agnieszka (University of Kansas)

Contribution ID: 13

Type: **not specified**

Preconditioned Iterative Methods for Weighted Toeplitz Least Squares Problems

Saturday, 11 June 2022 12:15 (30 minutes)

In this talk we consider the problem of finding effective preconditioners for linear systems of the form $Hx = y$ where

$H = A^T D A + \lambda^2 L^T L$ where A and L are structured matrices (e.g., Toeplitz), D is a diagonal matrix, and λ is a scalar. These linear systems can arise when iteratively computing approximations to nonlinear inverse problems. Typically in these applications the matrix D changes at each nonlinear iteration, but A and L remain constant. Benzi and Ng [1] considered linear systems of this form, and proposed an effective variant of constraint preconditioning and a Hermitian/skew-Hermitian splitting (HSS) preconditioner. In this talk we consider an alternative approach based on low-rank matrix approximations.

References

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Presenter: NAGY, James (Department of Mathematics, Emory University)

Contribution ID: 14

Type: **not specified**

Restarts for matrix Laplace transforms

Saturday, 11 June 2022 12:45 (30 minutes)

Let $A \in \mathbb{C}^{n \times n}$ be a matrix, $v \in \mathbb{C}^n$ a vector, and $f : D \subseteq \mathbb{C} \rightarrow \mathbb{C}$ a function defined on the spectrum of A . We consider the task of computing $f(A)v$, the action of the matrix function $f(A)$ on the vector v . This task arises in many applications and it is a viable alternative to computing $f(A)$ directly, which is impossible if A is large and sparse.

In this talk we consider the Arnoldi approximation, a Krylov subspace extraction for $f(A)v$. Since a new vector needs to be generated and stored in every iteration, one is often forced to rely on restart algorithms which are either not efficient or not stable or only applicable to restricted classes of functions. This holds already to some extent in the symmetric case, because of storage restrictions, and is very prominent in the non-symmetric case due to the increasing cost of orthogonalizations.

We present a new representation of the error of the Arnoldi iterates if the matrix function f can be represented as a Laplace transform

$f(t) = \int_0^\infty g(s)e^{-st} ds$, and develop a restarted algorithm for computing $f(A)v$ based on this error representation. The error is $\|f(t) - f_n(t)v\|$, and it generalizes earlier work of some of the author on quadrature-based restarts for Stieltjes matrix functions.

We will present several numerical experiments illustrating the efficiency of our approach, including fractional diffusion on graphs and the matrix Gamma function.

Presenter: FROMMER, Andreas (Bergische Universitaet Wuppertal)

Contribution ID: 15

Type: **not specified**

Anderson acceleration with approximate least-squares calculations: applications to scientific computing

Friday, 10 June 2022 18:30 (30 minutes)

We provide rigorous theoretical bounds for Anderson acceleration (AA) that allow efficient approximate calculations of the residual that reduce communication time and storage space while maintaining convergence. Specifically, we propose a reduced variant of AA, which consists in projecting the least squares to compute the Anderson mixing onto a subspace of reduced dimension. We numerically assess the performance of the reduced AA on: (i) linear deterministic fixed-point iterations arising from the Richardson's scheme to solve linear systems with open-source benchmark matrices with various preconditioners, (ii) non-linear deterministic fixed-point iterations arising from non-linear time-dependent Boltzmann equations, and (iii) non-linear stochastic fixed-point iterations arising from the training of neural networks. The dimensionality of the subspace onto which the least-squares to compute AA is projected adapts dynamically at each iteration as prescribed by computable quantities derived from the theoretical error bounds. The results show a reduction of the computational time without compromising the final accuracy.

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Contribution ID: **16**

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Opening

Friday, 10 June 2022 14:45 (15 minutes)

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Welcome remarks

Friday, 10 June 2022 14:30 (15 minutes)

Presenter: AMBROSIO, Luigi (Scuola Normale Superiore, Pisa)