2nd Workshop

on

Model Reduction of Complex Dynamical Systems (ModRed)

December 11-13, 2013
Max Planck Institute for Dynamics of Complex Technical Systems
Sandtorstraße 1
39106 Magdeburg

Program

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Collection of Abstracts

Invited Talks

Model Order Reduction Techniques for the Numerical Analysis of Linear Microwave Structures

Romanus Dyczij-Edlinger[1] Ortwin Farle[2] Alexander Sommer[3]

To demonstrate the great utility of model order reduction (MOR) techniques in the numerical analysis of electromagnetic structures, we consider a three-dimensional antenna array: It comprises a large number of radiators and features complicated shape as well as inhomogeneous material properties. The radiators are fed by waveguides, such as microstrip lines or hollow guides. As a general methodology for characterizing such structures, we propose finite-element (FE) modeling with subsequent (parametric) MOR.

The first focus of the talk is the efficient computation of the circuit response over a wide frequency range, where the ports of the circuit description correspond to propagable or weakly damped waveguide modes. In general, the modal waveforms are frequency-dependent and their propagation coefficients highly dispersive. To model such behavior, we formulate a two-dimensional eigenproblem for eigenpairs of waveforms and propagation coefficients, featuring the frequency as a parameter. To solve this eigenproblem over the parameter range of interest, we propose a self-adaptive multi-point MOR method and a suitable error indicator. Herein, one particular challenge arises from the non-trivial null-spaces of the differential operators involved. Once the eigenmodes are available, mode-specific boundary conditions for the driven FE model of the antenna structure can be formulated. Then, a fast frequency sweep for the antenna fields and circuit response is computed by means of a dedicated MOR method.

In addition to circuit parameters and near-fields, the far-fields seen from different look angles, i.e. the antenna pattern, are of great interest to radio engineers. Since antenna arrays allow electronic beam steering by changing the phase differences of individual radiators, the mathematical model exhibits five parameters: two steering angles, two look angles, and the frequency. We discuss MOR techniques for computing antenna patterns, present provable error bounds for the entire MOR process including the near-field-to-far-field transformation, and propose efficient techniques for computing such estimates.

Electromagnetic structures may also feature parameters such as material properties or geometrical design variables. In the latter case, the occurrence of non-affine parameters stemming from the geometry discretization of the FE method poses a particular challenge. We will present suitable MOR methods for affine and non-affine parameters and demonstrate the preservation of important system properties, such as passivity. Selected numerical examples conclude the talk.

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Overcoming the computational complexity of reduced basis methods for high-dimensional parameter spaces.

Jan S. Hesthaven[1]

While the application of certified reduced basis methods spans an increasing array of problem types, the computational challenges associated with high-dimensional parameter spaces remain very significant.

In this presentation we shall elaborate on some of the main bottlenecks associated with the high-dimensional case and discuss a number of different ideas that allow for substantial reductions in the offline or online stages of the reduced basis methods. We consider the use of adaptive sampling in the greedy approximation and the development of ANOVA based techniques in combination with reduced basis methods to compress the parameter space, allowing for a substantial acceleration of the method, both at the offline and the online stage.

Time permitting we shall also discuss an entirely different approach, suitable for problems with many components, and demonstrate the potential for a substantial parameter without impacting the overall predictive accuracy of the system response.

The efficiency and generality of the proposed techniques will be illustrated through a number of different applications, focusing on wave problems.

This work is done in collaboration with B. Stamm (UC Berkeley) and S. Zhang (Brown).

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Recent advances in the reduction of frequency based models for structures and vibrations

Karl Meerbergen[1]

Models in the frequency domain that arise in acoustics and structures are usually described by second degree matrix polynomials. More and frequently, models arise that have nonlinear frequency dependency, e.g., due to damping terms of visco-elastic structures. In addition, uncertainty quantification has also entered to the world of acoustics and vibrations. In particular, the damping terms are often subject to uncertainties. In this talk, we present an overview of techniques that were proposed the last three years for nonlinear frequency dependencies and parametric models. Most effort will be spent on Krylov methods but we will also give an overview of recent work on the dominant pole algorithm.

For nonlinear models, we will present a new class of methods, based on Hermite interpolation using Newton polynomials basis functions, which, embedded in a rational Krylov setting leads to a dynamic and reliable approach for model order reduction. The idea is based on the fact that when the poles of the rational Krylov method are chosen equal to the interpolation points, i.e., the nodes of the Newton polynomials, the nodes (both number and location) can be chosen dynamically during the execution of the algorithm.

For parametric models, we will discuss a new method for building the reduced model for the mean behaviour of a linear system with stochastic parameters. This problem can easily be expressed as a single input single output system using tensor notation, where the tensor represents the parameter dependent state vector. This leads to a two sided tensor Krylov method. We show a connection with multivariate interpolation methods.

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Contributed Talks

Interpolatory Model Reduction Techniques for Linear Second-Order Descriptor Systems

Mian Ilyas Ahmad[1] Peter Benner[2]

Standard interpolatory subspaces for model reduction of linear descriptor systems may produce unbounded $\mathcal{H}_2$ or $\mathcal{H}_\infty$ error. In this paper we investigate this issue and discuss modified interpolatory subspaces based on spectral projectors that ensure bounded error. In the special case of index-3 descriptor systems, we show how to transform the system to an equivalent system that enables the use of standard interpolatory subspaces for model reduction with bounded error, but without the explicit computation of spectral projectors. The approach can also be used to update interpolation points in the framework of $\mathcal{H}_2$ norm, thus extending the Iterative Rational Krylov Algorithm (IRKA) to index-3 descriptor systems. Also it is shown that the index-3 structure of the actual system can be preserved in the reduced order interpolating approximation.

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The Loewner framework for MOR of linear and nonlinear systems

Athanasios Antoulas[1] Cosmin Ionita[2]

Parametrized model order reduction (PMOR) addresses the problem of finding reduced-order models that accurately capture the behavior of parameter-dependent, large-scale systems. A new method for PMOR was recently introduced which uses the Loewner framework (PMOR-L). In this talk we will present an extension of PMOR-L to nonlinear systems.

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A survey about moment-matching model order reduction in computational electromagnetism

André Bodendiek[1] Matthias Bollhöfer[2]

The application of moment-matching methods for model order reduction has been widely discussed in the literature. In this talk, we will provide a survey of moment-matching methods in model order redution of Maxwell's equations. For a Greedy-type expansion point selection strategy, the adaptive-order rational Arnoldi (AORA) method represents an efficient way of computing the Galerkin projection. Since the main computational effort of the AORA method results from the subsequent solution of high-dimensional shifted linear systems, we provide a comparison with different recycling Krylov subspace methods. Moreover, an analysis about the efficient preconditioning of a complex symmetric, but highly-indefinite second-order Maxwell's equations for different expansion points will be given. Finally, different numerical experiments indicate the reliabilty of the application of moment-matching methods in model order reduction.

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Model Order Reduction for Uncertainty Quantification in Electric Field Simulations of High-Voltage Insulators with Nonlinear Resistive Electric Field Stress Grading

Markus Clemens[1] Daniel Schmidthäusler[2] Sebastian Schöps[3]

The numerical simulation of novel electric field insulators with resistive field stress grading and of surge arrestors requires the solution of electro-quasistatic field problems. The simulation must be carried out in the time domain due to the nonlinear resistive electric field grading materials, i.e., large nonlinear systems of ordinary differential equations are to be solved numerically. Naturally, the numerical solution depends on the input parameters, e.g., geometry and material data. In particular the material relations are affected by inaccuracies, for example due to manufacturing tolerances. This is crucial for resistive electric field grading materials since their degree of uncertainty is rather high: these materials are composites and their specific mixture determines the electric switching point. The production process of those materials is difficult to control. Consequently, each insulator will have a slightly different material configuration. To this end, the switching point is modelled as a random variable, which is e.g. normally distributed. The aim is to determine the random distribution (typically mean and standard deviation) of the electromagnetic field or other quantities of interest. This knowledge allows designers to develop more robust prototypes and may be an ingredient for guaranteed quality ("six sigma quality"). In order to reduce the high numerical costs of classical methods like Monte Carlo the framework of Polynomial Chaos and Model Order Reduction (POD) is used. To ensure the correctness of the uncertainty analysis, the nonlinear domains are excluded from the reduction and POD is applied only in subdomains with constant material properties, e.g., air or vacuum. In these exterior domains the degrees of freedom can be reduced significantly by the proper orthogonal decomposition method without significant loss of accuracy. The method involves a singular value decomposition to capture the system dynamics such that it extracts the essential dynamical behavior with a low number of degrees of freedom. Finally, only a few full simulations are necessary while most evaluations are carried out with the reduced model.

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An a posteriori error bound for linear parametrized systems

Lihong Feng[1] Peter Benner[2]

Parametric model order reduction (PMOR) is an advanced model order reduction technique for parametrized systems, which preserves the parameters as symbolic quantities in the reduced model, such that only a single reduced model is sufficient for all possible variations of the parameters.

In this work, motivated by an idea from [1], an a posteriori output error bound is derived for the reduced model of parametrized linear dynamical systems, whose bilinear form in the functional space may be unknown. For such dynamical systems, the error estimation used in the reduced basis community [1,4] is difficult to be applied, since it always requires the knowledge of the bilinear form (associated with the finite element discretization). The proposed error bound is an error estimation for the transfer function of the reduced model, and is derived directly in the vector space for the discretized system, without knowing any property of the original PDEs. Most importantly, under the guidance of the error bound, a reliable reduced model can be obtained automatically, using the Krylov subspace based PMOR method [2,3], by adaptively selecting the expansion points for the parameters as well as the Laplace variable. Simulations show that the error bound is promising for predicting the accuracy of the reduced model.

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$\mathcal{H}_2$-optimal model reduction of parametric elastic bodies

Michael Fischer[1] Serkan Gugercin[2] Peter Eberhard[3]

For the efficient simulation of mechanical systems the method of elastic multibody systems is frequently used. This approach, described by Schwertassek and Wallrapp, enables the description of large nonlinear rigid body motions as well as elastic deformations which is of increasing importance in many engineering fields, e.g. robotics, automotive and power engineering. Due to the fine spatial discretization of the elastic body for the Finite Element Method, linear model order reduction techniques are often applied to the arising second order system

$$\begin{aligned} \mathbf{M}_e \cdot \ddot{\mathbf{q}}(t) + \mathbf{D}_e \cdot \dot{\mathbf{q}}(t) + \mathbf{K}_e \cdot \mathbf{q}(t) &= \mathbf{B}_e \cdot \mathbf{u}(t), \\ \mathbf{y}(t) &= \mathbf{C}_e \cdot \mathbf{q}(t). \end{aligned} \tag{0.1}$$

The $\mathcal{H}_2$-optimal reduction with the Iterative Rational Krylov Algorithm (IRKA), described by Gugercin, Antoulas and Beattie, enables the determination of a reduced system which provides, at least, locally $\mathcal{H}_2$-norm optimal approximations to the original system. This approach is extended by Baur et al. to parametric systems with linear parameter dependency $\mathbf{p}$ only in the input-to-state matrix $\mathbf{b}(\mathbf{p}) = \mathbf{b}_0 + p_1\mathbf{b}_1$, and in the state-output-matrix $\mathbf{c}(\mathbf{p}) = \mathbf{c}_0 + p_2\mathbf{c}_1$ by defining a composite $\mathcal{H}_2 \otimes \mathcal{L}_2$-system norm

$$||\mathbf{H}||^2_{\mathcal{H}_2 \otimes \mathcal{L}_2(D)} = \frac{1}{2\pi} \int_{-\infty}^{\infty} \iint_D |\mathbf{H}(i\omega, \mathbf{p})|^2 dA(\mathbf{p}) d\omega \tag{0.2}$$

and enables producing a locally optimal parametric model in this composite error measure.

The force position on an elastic body can vary and is described with a parameter dependent input matrix $\mathbf{b}_e(\mathbf{p})$. In this contribution, the method described by Baur et al. is extended for mechanical systems with the transfer function

$$\mathbf{H}(s, \mathbf{p}) = \mathbf{c}_e(\mathbf{p}) \cdot (s^2\mathbf{M}_e + s\mathbf{D}_e + \mathbf{K}_e)^{-1} \cdot \mathbf{b}_e(\mathbf{p}) \tag{0.3}$$

to minimize the $\mathcal{H}_2 \otimes \mathcal{L}_2$-norm. The direct application of IRKA for second order systems and the investigation of mechanical systems of varying size and complexity will be presented. The quality of the reduced system is determined in comparison to reduction techniques based on the Component Mode Synthesis and Gramian matrices, which are described for elastic multibody systems by Fehr.

The definition of the parameter dependent input matrix for the force varying position problem $\mathbf{b}_e(p) = \sum_i^k \omega_i(p)\mathbf{b}_{e,i}$ with weighting functions ω_i requires an additional adaption of the calculation of the alternative weighted MIMO system.

References:

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Nonlinear Reduced Order Modeling for compressible transonic flows via Manifold Learning

Thomas Franz[1] Ralf Zimmermann[2] Stefan Görtz[3]

Many important aerodynamic engineering applications such as design, optimization, or aero-loads prediction require a large number of solutions to the compressible Navier-Stokes equations at varying aerodynamic conditions. As a consequence, very fast, yet sufficiently accurate Reduced Order Models (ROMs) are sought after.

A powerful tool for the order reduction of large-scale systems is Proper Orthogonal Decomposition (POD). Even though applicable to nonlinear problems, the main drawback of POD is the underlying assumption that the flow solutions lie in (or at least close to) a low-dimensional *linear subspace* spanned by preselected full-order CFD flow snapshots. Therefore, highly nonlinear features such as shocks are often insufficiently reproduced.

In this talk, we will present ROMs, which feature an improved shock prediction behavior. To this end, we replace the linear order reduction technique of POD by the nonlinear manifold learning method Isomap.

Manifold learning methods are widely used in the field of data and image processing. Here, the basic assumption is that the full-order data lie on a *nonlinear manifold* of low dimension. The transfer to fluid flow problems, however, poses several challenges:
(1) In the context of data analysis, only the mapping from the high-dimensional snapshot space to a low-dimensional representation is of interest, yet ROMs of the Navier-Stokes equations are required to deliver approximate flow solution of the same type and dimension as the full-order CFD solver. Hence, the inverse mapping (low-dimensional space to high-dimensional space) becomes essential.
(2) For data analysis applications, there is usually a vast amount of full-order input data. In contrast, when constructing CFD ROMs, it is tried to compute as few full-order solutions as possible due to the high cost of computing a single CFD solution.

In the talk, we will tackle the above challenges. As a numerical test case, the flow around the LANN airfoil in the transonic flow regime under variations of the angle of incidence and the Mach number is considered.

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Structure-Preserving Model Reduction for Nonlinear Port-Hamiltonian Systems

Serkan Gugercin[1] Christopher Beattie[2] Saifon Chaturantabut[3]

Modeling and simulation often follows a system-theoretic network modeling paradigm that formalizes the interconnection of naturally specified subsystems. If the core dynamic models of subsystem components arise from variational principles, the aggregate system model typically has structural features that characterize it as a *port-Hamiltonian (PH) system*. These systems generalize the classical notion of *Hamiltonian systems*, and are always *stable* and *passive*. Moreover, connecting PH systems together produces an aggregate system that is also port-Hamiltonian, and hence, it must be both stable and passive. This last fact provides compelling motivation to preserve structure when producing reduced order models for port-Hamiltonioan systems.

In this talk, we present a structure and stability preserving model reduction approach for large-scale nonlinear Port-Hamiltonian systems with an a-priori error bound. Two techniques for constructing reduced-order bases are considered: Proper orthogonal decomposition (POD) and a combined POD and quasi-optimal H2 model reduction. The nonlinear term is reduced efficiently using an extension of the discrete empirical interpolation method (DEIM). Numerical tests are shown using a nonlinear ladder network and a Toda lattice model with exponential interactions.

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Hierarchical Model Order Reduction of Systems under Parameter Variations

Matthias Hauser[1] Dr. Patrick Lang[2] Dr. Christian Salzig[3]

The trend from micro- to nanoelectronics complicates the design of analog circuits. The common modeling via nominal systems reaches its limit, since process variations in production and running of semiconductor devices are neglected. This leads to a drastic increase of the percentage of produced circuits whose characteristics are beyond their specifications. To counter that reduced models of analog circuits are needed that take also process variations into account. Furthermore the increasing size of modern analog circuits slows down the model order reduction itself. Thus a new concept is presented that uses the circuit's hierarchical structure to accelerate its model order reduction to generate reduced behavioral models of analog circuits under process variations.

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Reduced Basis Modeling for Time-Harmonic Maxwell's Equations

Martin Hess[1] Peter Benner

The Reduced Basis Method generates low-order models for the efficient evaluation of parametrized PDEs in many-query and real-time contexts. The approximation quality is certified by using rigorous error estimators.

We apply the Reduced Basis Method to systems of Maxwell's equations arising from electrical circuits. Using microstrip models, the input-output behaviour of interconnect structures is approximated with low order reduced basis models for a certain frequency range, parametrized geometry, like distance between microstrips and material coefficients. The models have been developed as part of the MoreSim4Nano project (www.moresim4nano.org).

We show the theoretical framework in which the Reduced Basis Method is applied to Maxwell's equations and present numerical results on the approximation quality, the efficiency of the error estimators and compare the performance of different Reduced Basis spaces (Lagrange Reduced Basis spaces versus Taylor Reduced Basis spaces).

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Combined Reduction for EEG Model Inversion

Christian Himpe[1] Mario Ohlberger[2]

Inverting EEG data of multiple sources to determine connectivity between brain regions is a complex problem even with few sources. Based on the Jansen and Rit Model, the Dynamic Causal Modelling (DCM) approach [1] employs a derived EEG model for multiple brain regions. The DCM-EEG model is a highly parametrized nonlinear second-order control system, which undergoes bayesian inversion to fit experimentally observed data to infer these regions connectivity. To be able to optimize the (posterior) distribution on the parameters swiftly, here a combined reduction of state and parameter space is proposed. The combined reduction [2] is accomplished employing empirical gramians introduced in [3]; these allow the (balanced) truncation of less important states and the lumping of redundant parameters. Originally only for state space reduction, the enhanced empirical gramians incorporate also parameter identifiability or sensitivity. Using the empirical gramian framework - `emgr` (see [4]), the combined reduction of the linearized and nonlinear DCM-EEG model is demonstrated, compared and evaluated.

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Finding the Characteristics: Radial Basis Function Interpolation for Parametric Model Order Reduction

Nils Hornung[1] Peter Benner[2] Sara Grundel[3]

We are interested in parametric linear time-invariant systems with inputs and outputs where the system matrices depend smoothly on one or more parameters. In order to create a parametric reduced order model that is close to $\mathcal{H}_2$-optimal, it is a natural choice to combine Radial Basis Function (RBF) interpolation with Krylov subspace based methods. Among the available approaches we particularly consider the Iterative Rational Krylov Algorithm (IRKA). Several ways to apply RBF techniques together with IRKA are compared, problems as well as possible solutions are discussed. We conclude with results from a variety of test applications.

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Reduced basis method for the solution of parametrized multiobjective problems

Laura Iapichino[1] Stefan Volkwein[2] Stefan Ulbrich[3]

We present a reduced framework for the numerical solution of PDE-constrained multiobjective optimization, where several objective functions have to be simultaneously optimized. The idea is to find a solution which does not penalize the optimization of any objective function and which is a good compromise for all the individual ones. In general, does not exist a single optimal solution, but there exists a (possibly infinite) number of Pareto optimal solutions. In the multiobjective optimization theory, the Pareto optimality [1] allows to determine efficient optimal points for all the considered objective functions. We apply the reduced basis method [3] in this context where the constraints are given by parametric PDEs, in order to propose a reduced-order techniques to handle the computational complexity and resolution times and to ensure a suitable level of accuracy taking into account the rigorous a posteriori error analysis developed in [2].

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Model order reduction and dynamic iteration for coupled systems

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The network approach to the modeling of complex technical systems results frequently in large coupled systems. There are different methods for solving such systems efficiently by using the structure and/or a model order reduction technique. In this talk, we present three model reduction based simulation approaches for coupled systems and demonstrate their behavior using a real life example.

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On stability and passivity in model reduction: A generalized SVD-Krylov approach

Marcus Köhler[1]

Reduction of linear time-invariant systems $S = (E, A, B, C, D)$ described by

$$\begin{aligned} E\dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned}$$

with $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, $y(t) \in \mathbb{R}^p$ and transfer function $G\colon s \mapsto C(sE - A)^{-1}B + D$ is discussed. The reduced system is $S_k := (V^\top X^\top EV, V^\top X^\top AV, V^\top X^\top B, CV, D)$. Matrix $V \in \mathbb{R}^{n\times k}$ corresponds e.g. to k interpolation points of G. Matrix $X \in \mathbb{R}^{n\times n}$ is either a solution of a Lyapunov equation to preserve stability or of a Riccati equation to preserve passivity and bounded realness, respectively. A possibly all-pass property of G is also kept. This method involves SVD-Krylov based methods [1] and interpolation of spectral zeros [2].

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GNAT for MOR of electrical networks with semiconductors

Ulrich Matthes[1] Michael Hinze[2]

We propose the Gauß-Newton with approximated tensors (GNAT) method to reduce electrical networks with semiconductors. We discuss the advantages and shortcomings of the approach and also provide a comparisson with reduction results obtained by the POD-DEIM approach proposed by Chaturantabut and Sorensen.

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Analysis of dry impacts on the basis of reduced elastic bodies

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For mechanical systems which undergo large nonlinear working motions and small linear deformations the elastic multibody systems approach is often selected [1]. For modeling each flexible body, the multibody system is cut free and the elastic displacement field of a single body is approximated by the Ritz approach together with the finite element method to obtain the equation of motion of each body. The reduction of the large number of elastic degrees of freedom is fundamental for the use of flexible structures in the multibody simulation. The reduction by linear model reduction allows a more efficient simulation with sufficient accuracy. A special challenge is represented by simulations with impacts. To get accurate results for elastic multibody simulations with impacts, both the global elastic deformation and the local deformation at the impact area have to be approximated very well. In [2] it is shown that many modal shape functions are necessary for this. The use of alternative procedures in reducing the elastic body for impact simulations is untested and of great interest. The issue of impacts in association with model reduction is that there are many points on which forces may act, which means that one gets an input matrix containing several columns. Additionally, the output matrix contains also many rows, since it is necessary to observe the nodes at which the body is in contact. The aim of the contribution is to study the model reduction of flexible bodies in a pure impact problem with the background of many input and output variables. Here a comparison of non-modal reduction methods, [3], with modal methods is performed. The high number of inputs and outputs is accompanied by growing difficulties in the model order reduction process. Depending on the reduction method, a methodological and qualitative input/output dependency can be shown. As an example, using the Craig-Bampton reduction technique, the minimum reduction size is determined by the number of attachment points and inputs, respectively. Moreover, the establishment of criteria for assessing the quality of the reduced body with respect to the approximation quality of the impact is essential.

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Parameterised Model Order Reduction for Uncertainty Quantification

Roland Pulch[1]

We consider linear dynamical systems in form of ordinary differential equations or differential algebraic equations with high dimensionality. Physical parameters of the systems often exhibit uncertainties due to measurement errors or variability of a manufacturing process, for example. An uncertainty quantification is achieved by the introduction of random parameters. On the one hand, methods of Monte-Carlo type are applicable to the stochastic problems, where the original systems are resolved many times. On the other hand, a stochastic Galerkin approach based on a polynomial expansion yields a large coupled system to be solved once only. We investigate techniques of parameterised model order reduction to decrease the complexity of the stochastic models and thus to obtain efficient numerical methods. Here the reduced order models are reuseable for arbitrary realisations of the random parameters. The focus is on procedures, which include moment matching or balanced truncation in the reduction. We present results of numerical simulations for test examples.

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Projection-free balanced truncation for differential-algebraic systems

Timo Reis[1] Olaf Rendel[2]

We revisit the problem of balancing-related model order reduction for differential-algebraic systems. Based on alternative Lyapunov, Riccati and Luré equations, we will show that model reduction by balanced truncation can be done without explicit use of projectors onto the inherent dynamics.

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Implicit-IMOR method for linear constant Differential Algebraic Equations

Wil Schilders[1] Nicodemus Banagaaya[2] Giuseppe Alí[3]

In our previous papers, we proposed a new Moder Order Reduction (MOR) method specifically for differential algebraic equations (DAEs) which we call the index-aware model order reduction (IMOR) method. This method involves first splitting the DAE into the differential and algebraic parts using bases of special projectors. Then we apply the exist MOR methods for ODEs to reduce the differential part and develop techniques to reduce the algebraic parts. The IMOR method leads to simple and accurate reduced-order models. Moreover the IMOR method can be applied to higher index DAEs. However the IMOR method involves matrix inversions which may limit its practicality in some real-life examples. This motivated us to introduce a modification of the IMOR method which we call the Implicit-IMOR method which does not involve matrix inversions. We shall test the robustness of the Implicit-IMOR method using problems from computational fluid dynamics (CFD) community and electric network community.

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Uncertainty Quantification for order reduced Maxwell's equations

Judith Schneider[1] Peter Benner[2]

Nowadays, the design process of semiconductor structures is unimaginable without simulations of new micro and nano scale systems due to the expensive production of prototypes. However, the numerical simulation of systems which result from modeling of micro scale structures is computationally demanding. Two aspects make the simulation even more complicate. One is the ongoing miniaturization of the structures in combination with an increasing of the working frequencies. This implicates a high density of electric conductors and induces parasitic effects like crosstalk. To respect these parasitic effects, Maxwell's equations are considered for the simulation. Inaccuracies during the lithography which lead to variations of the feature structure sizes lead to another aspect that can no longer be neglected during the simulation. Besides that, material uncertainties have to be considered. These variations are treated as uncertain parameters of the system.

For the variational analysis of the effect of these uncertainties on the electromagnetic field we compare stochastic collocation techniques [1] to a Monte Carlo simulation [2]. Collocation methods rely on repetitive evaluations of the describing system of equations, which can be expensive for high dimensional systems. Therefore, we use model order reduction to reduce the size of the system and the evaluation costs. The reduced model is then used for Monte Carlo and stochastic collocation. We apply the described method to a coplanar waveguide and show the numerical results.

The work presented is part of the research network MoreSim4Nano [3], which is funded by the German Federal Ministry of Education and Research.

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Solving parametric algebraic Lyapunov equations using reduced basis method

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Our aim is to numerically solve parameter-dependent Lyapunov equations, especially those affinely depend on the parameters. Such equations arise in parametric model order reduction. We use the reduced basis method for the problem. For Lyapunov equations with symmetric positive definite matrix coefficients, we derive an *a posteriori* error estimate using min-Θ approach. With this error estimate, a Greedy algorithm for (*offline*) constructing the reduced basis is formulated. Numerical examples are presented.

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Model order reduction of mechanical systems subjected to moving loads by the approximation of the input

Alexander Vasilyev[1] Tatjana Stykel [2]

In this talk, we consider the problem of model order reduction (MOR) of mechanical systems subjected to moving loads. Such systems arise in the simulation of vehicle-bridge interactions, cableways or working gear wheels. Linear MOR techniques cannot be directly employed because of the time-dependence of the input and output matrices. However, this time-varying problem can be converted to that of time-invariant systems by approximation of the input matrix. We present some numerical results for a beam with simply supported ends subjected to a moving load. The principal difficulties in MOR of this model as well as the advantages and disadvantages of the presented MOR techniques are also discussed.

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Poles/residues optimization for frequency-limited H2 model approximation

Pierre Vuillemin[1] Charles Poussot-Vassal[2] Daniel Alazard[3]

Approximation of medium-scale linear dynamical systems over a bounded frequency range is considered as an optimization problem in terms of the frequency-limited H2-norm, denoted H2w-norm. This formulation enables to address the frequency-limited approximation problem without involving any filter, which alleviates this tedious choice and is appealing from an engineer point of view.

The H2w-norm can be expressed with the poles and associated residues of the system in a very similar way to the H2 norm, thus representing a natural generalization. As grounded on this norm's formulation, the frequency-limited approximation problem then consists in finding the reduced poles and residues that minimizes the H2w norm of the error. To this aim, the H2w-norm of the approximation error is expressed and the first-order optimality conditions, derived. These optimality conditions are then exploited in a complex-domain descent algorithm.

The proposed approach requires to solve one single large-scale eigenvalue problem and is thus dedicated to medium-scale models but if offers some interesting properties. Indeed, (i) the error is guaranteed to decrease, (ii) by increasing the order of the reduced-order model until the error falls under a specified value, the algorithm enables to work with a fixed H2w error instead of a fixed order and (iii) with only few additional costs, an a posteriori bound on the Hinf-norm of the error can be computed as well.

The proposed approach is illustrated through several standard numerical examples and is used in the industrial aerodynamical domain.

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Model reduction for optimal control problems in field-flow fractionation

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We discuss the application of model order reduction to optimal control problems governed by coupled systems of the Stokes-Brinkman and advection-diffusion equations. Such problems arise in field-flow fractionation processes for the efficient and fast separation of particles of different size in microfluidic flows. Our approach is based on a combination of the tangential interpolation and POD-DEIM techniques for model reduction of the semidiscretized optimality system. Numerical results demonstrate the properties of this approach.

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Cumulative model order reduction and solution of Lyapunov equations using Krylov subspaces and adaptive shift selection

Thomas Wolf[1] Heiko K. F. Panzer[2]

For Krylov-based model order reduction, the reduced order typically has to be chosen a priori. In this talk, we present a cumulative procedure based on projections onto Krylov subspaces, such that the reduced order is determined adaptively: the original model is reduced to very small order; a factorization of the resulting error system permits to conduct a second reduction step; by iterating this procedure, a total reduced system is found by accumulating independently reduced ones. Thereby, the main numerical effort remains the construction of the Krylov subspaces. Additionally, the cumulative procedure enables an adaptive shift selection by an independent optimization for each reduction step.

The above mentioned procedure can also be employed for the solution of Lyapunov equations: with projected matrices as its coefficients, a reduced Lyapunov equation can be solved by direct methods, providing an approximation of the solution in the high dimensional space. In a similar way to model reduction, a total approximation can be computed by accumulating independently reduced ones. If, furthermore, all reduction steps were performed in a distinct manner (so-called H2 pseudo-optimal), one can show that the resulting total approximation is equal to the application of the ADI iteration with the same set of shifts. This reveals the general connection between the ADI iteration and projective methods by Krylov subspaces. As a consequence, results on Krylov subspaces - as e.g. adaptive shift selection and tangential interpolation - can be formulated in an ADI fashion.

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A reduced basis method and ROM-optimization for batch chromatography

Yongjin Zhang[1]

In this work, a reduced basis method is applied to batch chromatography, and the underlying optimization is solved efficiently based on the resulting reduced model. More precisely, instead of solving the full system of equations, a reduced model with a small number of equations is derived by the reduced basis method, such that only the small reduced system is solved at each step of the optimization process. An adaptive technique of selecting the snapshots is proposed, so that the offline time is largely reduced. An output-oriented error bound is derived in the vector space whereby the construction of the reduced model is managed automatically. An early-stop criteria is proposed to circumvent the stagnation of the error bound and make the construction of the reduced model more efficiently.

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A parametric reduced order model for the linear frequency domain approach to time-accurate computational fluid dynamics

Ralf Zimmermann[1]

For transonic flows governed by the time-accurate Navier–Stokes equations, small, approximately periodic perturbations can be calculated accurately by transition to the frequency domain and truncating the fourier expansion after the first harmonic. This is referred to as the linear frequency domain (LFD) method. In this talk, a parametric trajectory of reduced order models (ROMs) for the LFD solver is presented. To this end, several local projection–based ROMs, which are essentially specified by suitable low-order subspaces, are computed by the method of proper orthogonal decomposition (POD) in an offline stage. The claimed trajectory is obtained by interpolating the given local subspaces considered as sample points in the Grassmann manifold. It will be shown that the manifold interpolation technique is restricted to a certain class of interpolation schemes. Moreover, it turns out that the application of computing accurate ROMs for the LFD solver requires a special choice of underlying inner product, necessitating a non-Euclidean approach. By exploiting a separable parametric dependency, real-time online performance is achieved. Numerical results are presented for emulating an airfoil in the transonic flow regime under a sinusoidal pitching motion.

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Information

On site

- Room:
  All talks will be given in the seminar room *Prigogine* on the ground floor of the MPI.

- Coffee breaks:
  Coffee, tea, soda, juice, and cookies will be served in the neighboring seminar room *Wiener*.

- Lunch breaks:
  Lunch, soda, and juice will be served in the neighboring seminar room *Wiener*.

- Posters:
  A small selection of posters is located around the bar tables in the entrance hall of the MPI. There will be no poster session but we hope to encourage fruitful discussions during the breaks.

- WLAN:
  Eduroam is available everywhere in the institute building. You may also obtain a guest account for the MPI guest net. For the account, you have to sign at the registration desk.

- Conference dinner:
  The conference dinner takes place at the Restaurant L∼BE at Wednesday evening. The dinner and the first drink are included in the conference fee.

- Christmas market visit:
  We suggest to visit the Christmas market (next to the tram stop *Alter Markt*) on Thursday evening.

For Speakers

- Please make sure that your presentation is transfered to the computer (Windows XP, Adobe Reader 11 and PowerPoint 2010) connected to the beamer before your session starts.

- Ask the local organizers if you have any questions.

Local organizers

- Prof. Dr. Peter Benner
- Martin Hess
- Diana Noatsch-Liebke
- Judith Schneider

Important phone numbers

- Emergency number: **112**
- MPI reception: **+49 (0)391 611 00**
- Taxi office: **+49 (0)391 565 650**

How to reach the MPI

- By airplane:
  The next airports are Berlin-Tegel, Hannover and Halle-Leipzig. All airports have a good train connection to Magdeburg.

- By train/ public transport:
  From Magdeburg Hauptbahnhof (central station) you go to *Damaschkeplatz* (tram stop is located behind the main station) or *Alter Markt* (5 minutes to walk) and use the MVB to reach the stop *Askanischer Platz* which is next to the MPI. Tram 5 goes directly from *Alter Markt* to *Askanischer Platz*. If you use the tram stop *Damaschkeplatz* you have to change lines. See the MVB maps for more information. There is also a taxi stand in front of the Hauptbahnhof (central station).

- By car:
  - coming from Hannover and Berlin: via highway A2 until the exit 70 (Magdeburg-Zentrum); follow B189/B71 (Magdeburger Ring) in south direction (Halle/ Halberstadt) until exit Universität/Zentrum-Nord; turn right on Albert-Vater-Straße, in east direction on Walther-Rathenau-Straße; just before the Jerusalembrücke (bridge over the river Elbe) turn left on Sandtorstraße.
  - coming from Halle: via highway A14 until the exit 5 (Magdeburg-Sudenburg/ Magdeburg-Zentrum); follow B189/B71 (Magdeburger Ring) in north direction (Hannover/Berlin) until exit Universität/Zentrum-Nord; turn right on Albert-Vater-Straße, in east direction on Walther-Rathenau-Straße; just before the Jerusalembrücke (bridge over the river Elbe) turn left on Sandtorstraße.

- From Hotel Ratswaage:
  Hotel Ratswaage is located close to the tram stop *Alter Markt*. You can take tram 5 to reach the stop *Askanischer Platz*.
  By foot you will need 15-20 minutes.

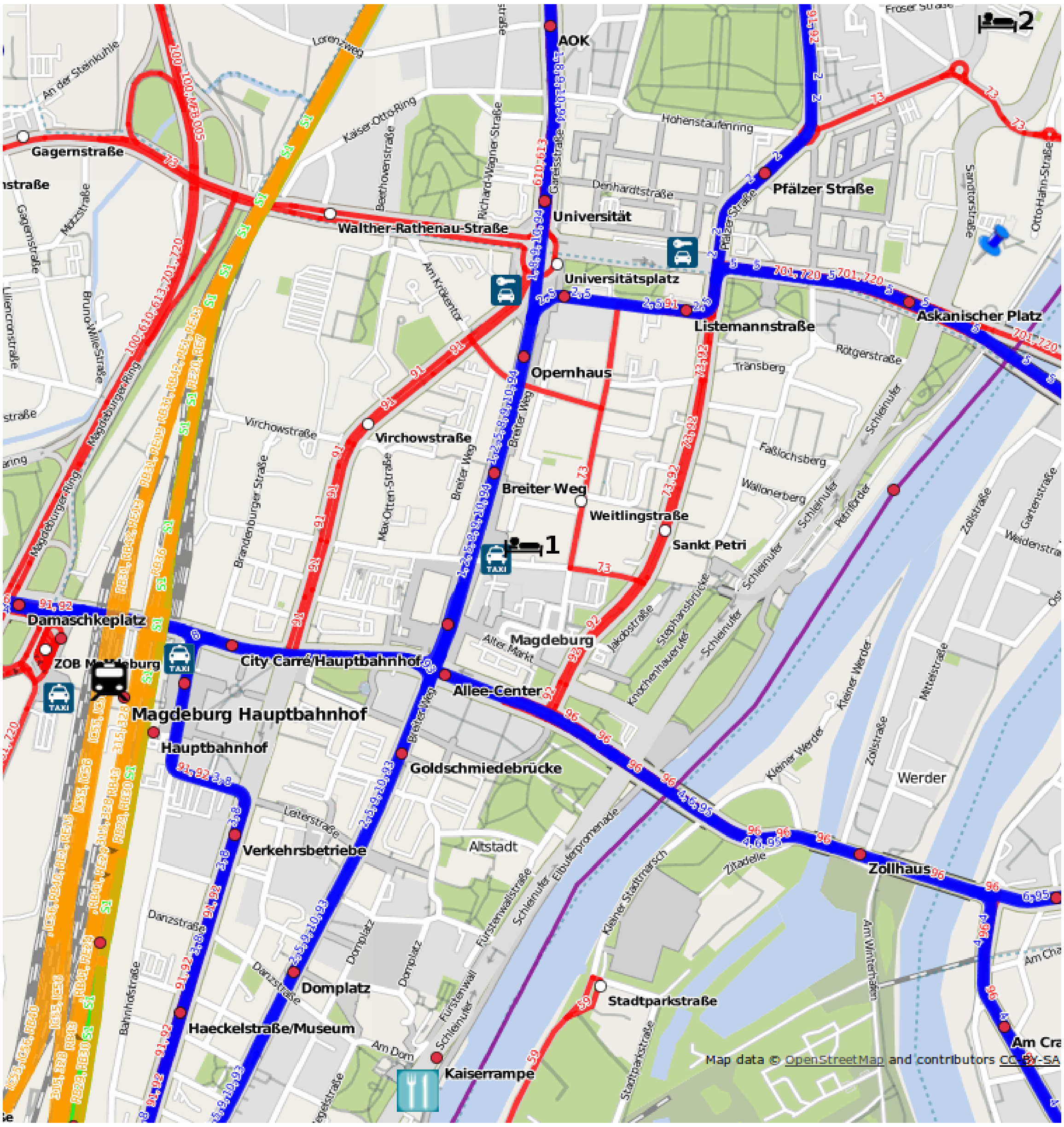
- From Hotel Sleep & Go:
  By foot you will need 5-10 minutes.

How to reach restaurant L∼BE (conference dinner)

- By tram:
  Take tram 5 from *Askanischer Platz* to *Domplatz* and take a 5-10 minutes walk passing by the cathedral.

- By foot:
  Take a nice 25-30 minutes walk along the river Elbe.

City Map



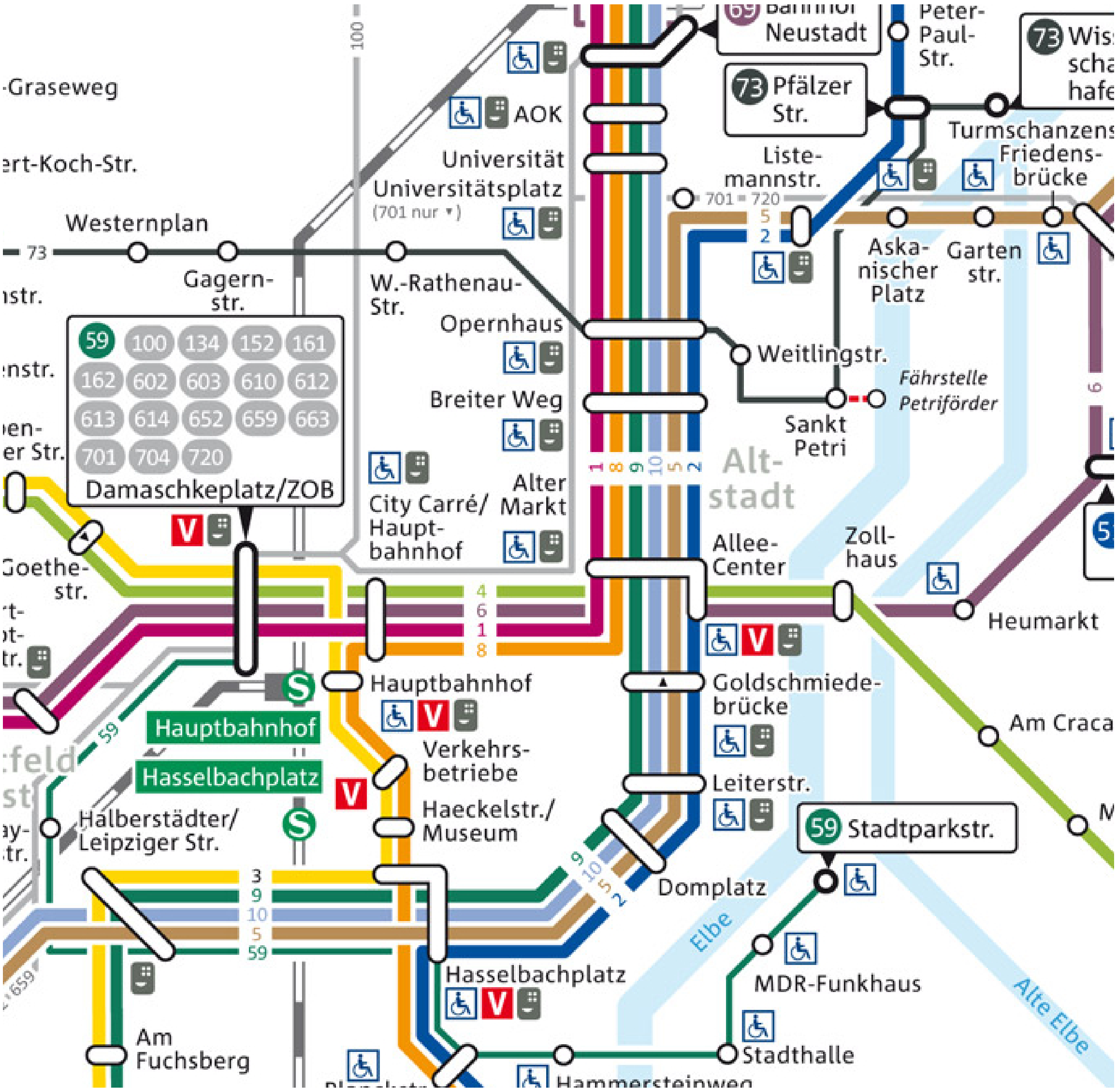
Max Planck Institute for Dynamics of Complex Technical Systems

Restaurant L∼BE (Conference Dinner)

1 Hotel Ratswaage

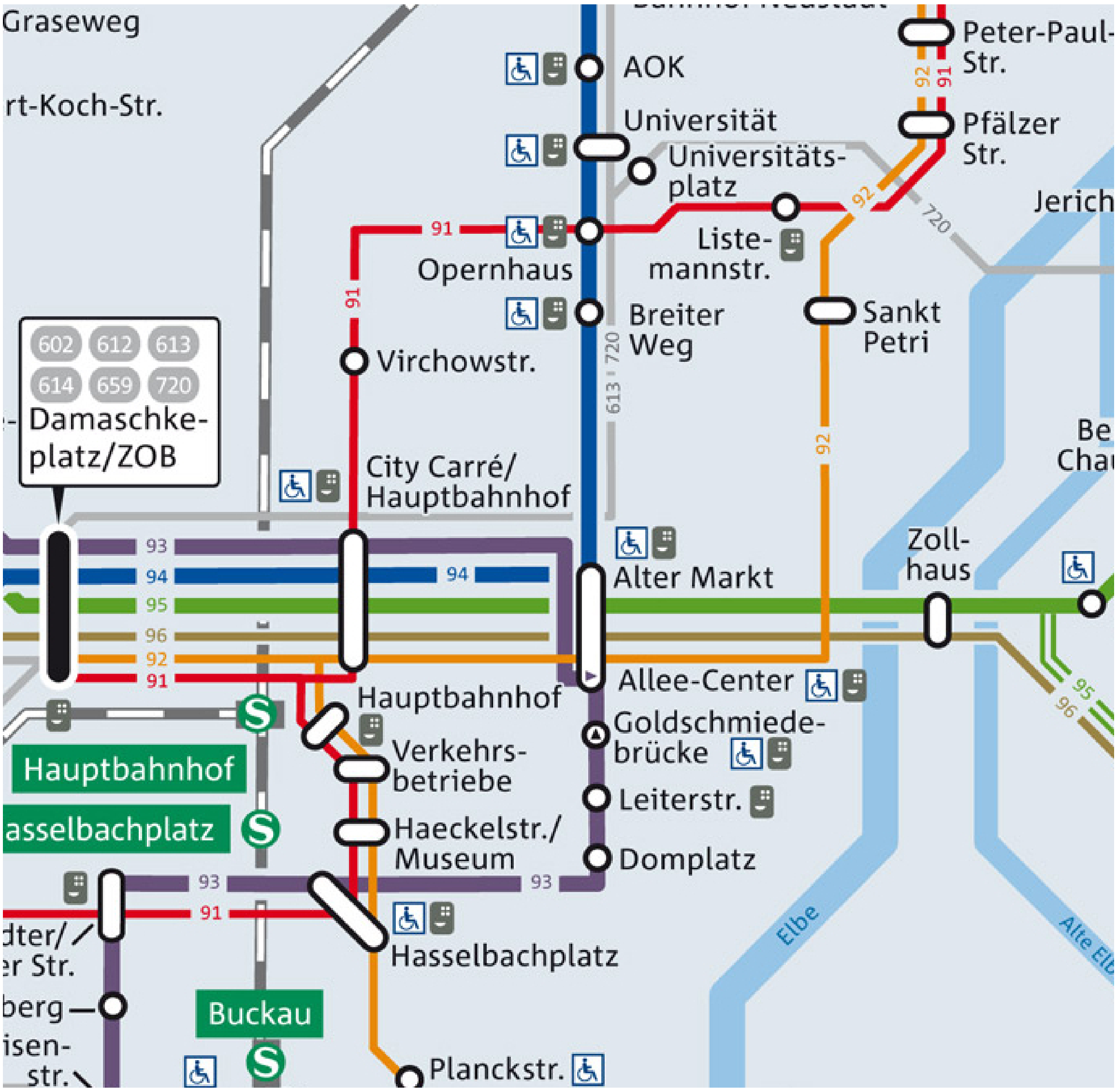
2 Hotel Sleep & Go

Extract of the MVB map (before 9 pm)



http://www.mvbnet.de/verkehr/liniennetzplaene/am-tag/

Extract of the MVB map (after 9 pm)



http://www.mvbnet.de/verkehr/liniennetzplaene/zum-anschlussverkehr/

Notes

Max Planck Institute for Dynamics of Complex Technical Systems
Computational Methods in Systems and Control Theory