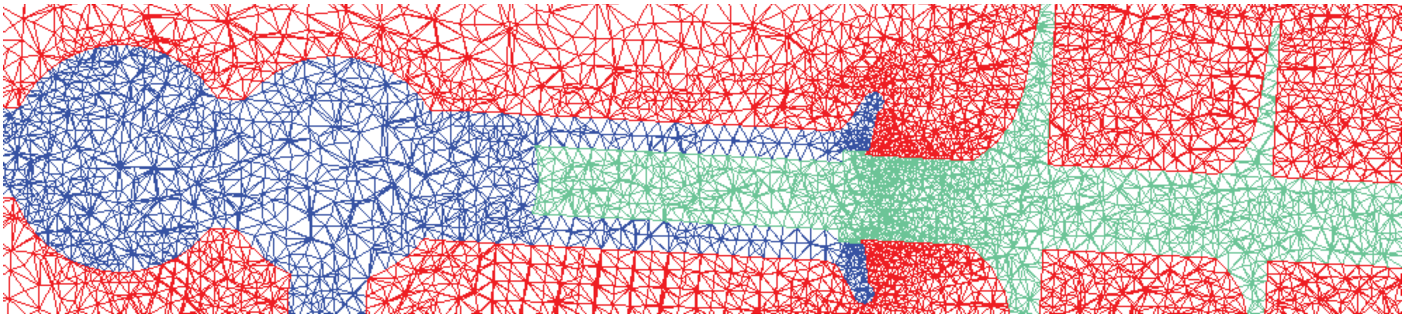


Modelling an invisible field

Professor Dr Markus Clemens uses mathematical equations and parallel computing techniques to model electromagnetic fields with applications across many disciplines

What first inspired you to work in electrical engineering?

My university education in applied mathematics came with a strong focus on mathematical modelling, ie. the translation of physical processes or technical real-world problems into a mathematical model consisting of complex sets of equations. The solutions to these equations are then determined by choosing suitable methods from numerical mathematics and computer science.

When I took up my PhD studies within the Institute for Theory of Electromagnetic Fields at the Technische Universität Darmstadt, I was fascinated by the fact that when these techniques were focused on the simulation of electromagnetic fields, they helped create flexible computer-aided engineering (CAE) software tools. These tools enable electrical engineers to solve complex and increasingly realistic problems in electrical engineering using virtual prototyping techniques.

How would you describe the ultimate goal of your research into computational electromagnetics (CEM) techniques?

The aim of CEM is to develop and apply CAE software tools that are capable of simulating any electrical or electronic device configuration that relies on electrodynamic field processes. These model-based virtual representations need to provide a suitable level of realism and should allow fast and robust computer model-based optimisations of sets of design parameters.

An optimal CEM technique should ultimately maximise accuracy in terms of how close the simulation is to reality and should minimise cost in terms of required simulation time, hardware requirements and the billable time of an engineer working on the problem. Thus, the 'optimal' CEM method may differ for each technical problem, and may also depend on available resources (eg. funds for soft- and hardware, manpower).

Can you expand on your recent discoveries relating to numerical methods for electromagnetic compatibility (EMC) testing?

EMC issues of technical devices or biological organisms often require realistic modelling of geometric details on multiple scales. This may result in large-scale computer simulation models with up to billions of unknowns. Modern graphics processing units (GPUs) allow us to significantly accelerate these numerical simulations. GPU multi-core parallelism also enables us, for example, to effectively use full-wave discontinuous Galerkin finite element method field simulation schemes with improved geometric modelling capabilities that are especially attractive for EMC-related problems.

Could you highlight the key benefits of using a numerical method such as the finite integration technique (FIT) for EMC testing? How is this different to the previous finite-difference time-domain (FDTD) method?

FIT is considered a natural, ie. structure preserving, direct reformulation of Maxwell's equations on a staggered grid pair using global quantities similar to network theory such as fluxes, currents, voltages and charges. The resulting matrix formulations of the FIT immediately allow the construction of numerical schemes that are conservative, ie. that naturally preserve quantities such as charge or energy. The discrete field theory framework of the FIT contains the FDTD method as a special case, but also extends to static and quasistatic field formulations, and enables the introduction of many extensions that further improve its practical applicability and accuracy, such as partially filled grid cells or local grid refinements.

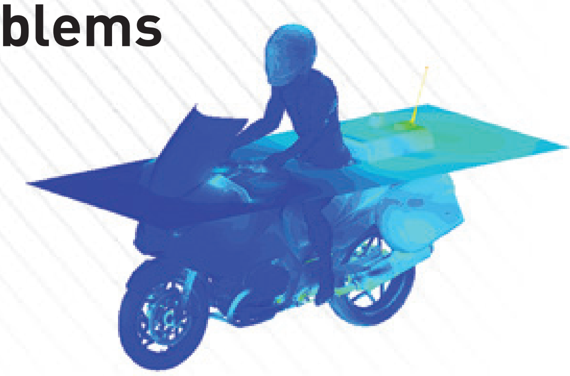
What particularly excites you about current CEM research?

CEM research requires a strong interdisciplinary approach: starting from a real-world engineering application, a corresponding mathematical model is created based on electromagnetic field theory, sometimes also with other physical domains. A computer-based simulation of this model then requires a selection of efficient numerical methods provided by applied mathematics. These need to be implemented with respect to results of computer science in terms of software and hardware design. This strong connection of electrical engineering, mathematics and computer science makes CEM an exciting field of ongoing research, despite the fact that 150 years have passed since the first publication of Maxwell's electromagnetic field theory.

Do you have any success stories from your research you would like to share?

The majority of our research is related to real-world problems and driven by projects with industry or federal agencies, but is always enabled by results of previous fundamental research efforts. A success story lies within our academic research on slowly varying electric and magnetic field simulation methods that led to the 3D FEM research code MEQSICO (Magneto-/Electro-Quasistatic SImulation COde). This software is used to simulate and optimise complex devices from electric power transmission, eg. polymeric long rod insulators or high voltage bushings featuring novel field stress grading materials, which are both now being tested as real-world prototypes. A similar development is imminent for numerical EMC testing methods, as these have now reached a level of maturity that makes them very interesting competitors to conventional measurement techniques.

Computational electromagnetics: solutions to multidisciplinary problems



Researchers from the **University of Wuppertal** in Germany are undertaking diverse projects in computational electromagnetics and computational engineering, ranging from developing new modelling methods to determining the effects of electromagnetic fields on biological systems

IN THE EARLY 1860s, Scottish physicist and mathematician James Clerk Maxwell developed a revolutionary set of equations that described and generalised the relationship between electricity and magnetism. These four simple partial differential equations combine laws in electromagnetism drawn up by 19th Century heavyweights Carl Friedrich Gauss, André-Marie Ampère and Michael Faraday, and are still used today to mathematically explain electrodynamic field behaviour.

By changing mathematical assumptions, such as geometries, material relations and boundary conditions, the equations can be put to use in many different contexts. For instance, solutions generated by Maxwell's equations fully describe electrical fields in high voltage transmission components, magnetic fields in electric motors or the electromagnetic field distribution of antennae. Over the last 50 years, physicists, mathematicians and computer scientists have refined these equations so that they can be used to solve more and more complex problems using computer models with billions of unknowns.

ENDLESS POSSIBILITIES

Led by Professor Dr Markus Clemens, researchers from the Chair of Electromagnetic Theory at the University of Wuppertal in Germany have been using new modelling techniques to solve Maxwell's equations to a superior level of resolution. While classic models can be solved using Maxwell's equations reasonably easily – sometimes even using a pencil and paper – more complex models must be solved using simplifying techniques that break the continuous dimensions of the real world into manageable chunks, ie. discretise the problem, so that computers are capable of processing and optimising it.

For many years, this was achieved using the finite-difference time-domain (FDTD) method. FDTD is a grid-based differential numerical modelling technique, and solutions can cover a wide frequency range in a single simulation run. Developed almost 50 years ago, the basic principles underlying this method still govern many commercial electromagnetic field simulation tools. Clemens and colleagues are instead using the finite integration technique (FIT), which is capable of solving the same situations as FDTD, but can be further specialised to improve accuracy and applicability by, for example, using partially filled grid cells. FIT extends the structural idea within FDTD, evolving it into a fully-fledged discrete electromagnetic field theory. The resultant computer-compatible Maxwell grid equations can be used to simulate very accurately real-world electrical, magnetic and electromagnetic field distributions in terms of geometry, material distribution and conservation of charge and energy.

APPLYING MATHEMATICS

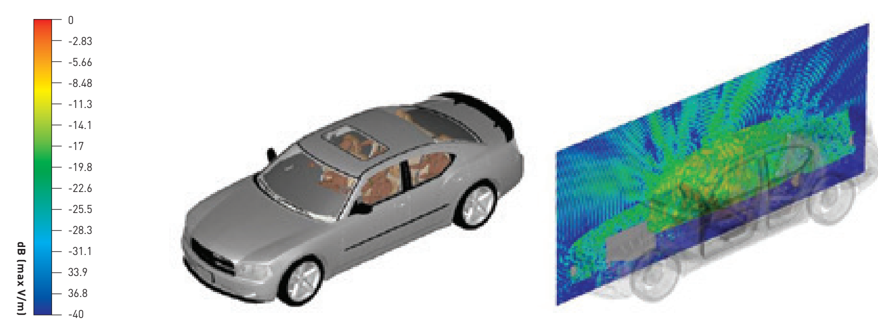
One area in which this technique can be applied is in simulating the exposure of biological organisms to electromagnetic fields, something that is usually impossible using conventional measurement methods. According to Clemens: "This approach, relying on high-fidelity field simulations with high-resolution tissue models, enables the safe analysis of the electromagnetic impact due to field sources such as radiating antennae or low frequency magnetic coils". For example, the Wuppertal collaborators have modelled a police motorcyclist sitting in front of a TETRA radio antenna in order to determine the specific absorption rate of the electromagnetic power as a source of increased local body temperature. Going further, they have also simulated a car with a mobile device radiating at 2 GHz with four high-resolution body phantoms.

These high-fidelity electromagnetic field simulations require 700 million and 1.5 billion FDTD grid cells, respectively – only made possible by a supercomputer acquired in 2013 by the University of Wuppertal's Interdisciplinary Center for Applied Informatics and Scientific Computing with a grant from the German Research Foundation (DFG). The supercomputer has eight nodes comprising about 1.2 TB of random access memory (RAM) and 40 NVIDIA K20 graphics processing unit (GPU) accelerators. This capacity has made it possible to consider problems at higher frequencies (smaller time steps) and with improved geometric resolution.

FIT AND FEM

Clemens and colleagues do not wed themselves solely to one technique, extensively utilising another specific volume discretisation procedure: the finite element method (FEM). FEM is more suited to the rapid calculation of slowly varying magnetic and electric fields, and is therefore ideal for the design and optimisation of electric power transmission components such as insulators, cable terminations or switches using modern hybrid materials.

Combining FEM with FIT and other computer-aided procedures with different resolution capabilities based on alternative formulations of Maxwell's equations offers new and powerful



Car model with mobile device radiating at 2 GHz simulated with 1.5 billion FDTD grid cells.

CASE STUDIES

Electromagnetic attacks – as part of the EU Seventh Framework Programme (FP7)-funded 'Strategies for The impRovement of critical infrastrUCTUres Resilience to Electromagnetic attackS' (STRUCTURES) project, the Wuppertal researchers have used their multi-method approach to model electromagnetic coupling paths into buildings and technical systems – including control centres, banks and airports – which could be vulnerable to electromagnetic attacks.

www.structures-project.eu

Body scanners and cancer diagnosis – working alongside Wuppertal colleague Professor Dr Ullrich Pfeiffer, Clemens and colleagues have developed and applied methods to assess exposure to non-ionising radiation at frequencies in the terahertz range. This range is increasingly being explored for airport security body scanners and for new cancer diagnostics.

Mobile phone risk assessment – the World Health Organization (WHO) claims there is a paucity of information on the risks to children of regular and targeted exposure to electromagnetic radiation. Addressing this, researchers from Jacobs University Bremen together with Clemens and colleagues from Wuppertal conducted a study on behaviour and memory of head-only exposed continuously growing rats. They found no harmful effects from long-term exposure on subsequent development, learning skills and behaviour. Recently, the same team replicated an older study performed at Fraunhofer ITEM Hannover showing tumour-promoting (not inducing) effects in carcinogen-treated mice during lifelong exposure to electromagnetic radiation.

High voltage – in collaboration with Lapp Insulators GmbH, an international manufacturer and supplier of high voltage insulators, the Wuppertal team has investigated in detail how to damp the electric field intensity within a device called a 'bushing' that prevents electrical energy from conducting to the nearest earthed material and therefore causing burning and arcing. This collaboration has expanded to include improving the longevity and providing a more compact layout for Lapp Insulators' electric high voltage component technology.

Vehicle design – the Federal Ministry of Education and Research (BMBF)-funded SOFA project is an academia-industry collaboration to develop coupled simulation and optimisation techniques, including methods and software tools for efficient and robust virtual vehicle design, with a focus on electromagnetic compatibility. Such progress should increase speed to market and decrease design costs.

www.sofa-verbund.de

Model of police motorcycle with radiating TETRA antenna next to a transporter.

ways of simulating complex electromagnetic problems at multiple scales or in multiple domains. With the development of efficient simulation methods and algorithms being another focus, Clemens and colleagues are undoubtedly at the forefront of computational electromagnetics science.

LOOKING AHEAD

Computational electromagnetics offers solutions to a wide range of real-world challenges. These solutions have become advanced enough that many are available in commercial simulation codes. However, research within the field is far from dying down and, looking to the future, three areas will be a primary focus. First, the development of new applications in electrical engineering, such as terahertz devices, nanoscale devices or devices using new materials, will challenge current capabilities in computational electromagnetics and require further research. Second, coupled 'multi-something' problems such as multi-physics/-scale/-domain/-grid problems will require the development of more advanced multi-method approaches. Third, research into more 'computer compatible' electromagnetics formulations will be necessary because of ongoing computer hardware development which, at the moment, is focused on multi-core architectures.

Clemens and colleagues are interested in diverse problem-solving applications with computational electromagnetics and electrical engineering and are constantly searching for new projects. Partnerships under the auspices of the EU Horizon 2020 framework or through ad hoc bilateral agreements are definite possibilities for this diverse team, which already collaborates with several industry partners.

INTELLIGENCE

COMPUTATIONAL ELECTROMAGNETICS – MODELLING AND SIMULATION OF ELECTROMAGNETIC FIELDS

OBJECTIVE

To develop and apply computer-aided engineering (CAE) software tools that are capable of simulating any electrical or electronic device configuration relying on electrodynamic field processes.

TEAM MEMBERS

For a full list of team members, please visit:
www.tet.uni-wuppertal.de/en/nc/staff

PARTNERS

For a full list of academic and industrial partners, please visit:
http://bit.ly/clemens_partners

FUNDING

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Federal Office for Radiation Protection (BfS)

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PROFESSOR DR MARKUS CLEMENS gained a university diploma in Mathematical Engineering (1995, University of Kaiserslautern), followed by a PhD in Computational Electromagnetics (1998, Technische Universität Darmstadt). He is Head of the Chair of Electromagnetic Theory and Vice Dean of Faculty E at the University of Wuppertal, Germany. His research interests are in computational electromagnetics and the application of modelling and software tools for electromagnetic fields.

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