

# GECEM: Grid-Enabled Computational Electromagnetics

David W. Walker and Jonathan P. Giddy  
School of Computer Science  
Cardiff University  
PO Box 916  
Cardiff CF24 3XF

Nigel P. Weatherill and Jason W. Jones  
Civil and Computational Engineering Centre,  
School of Engineering  
University of Wales Swansea  
Swansea SA2 8PP

Alan Gould, David Rowse, and Michael Turner  
BAE SYSTEMS  
Advanced Technology Centre, Filton  
Bristol, BS34 7QW

## Abstract

*The GECEM project aims to use and develop Grid technology to enable large-scale and globally-distributed scientific and engineering research. The focus of the project is collaborative numerical simulation and visualisation between the UK and Singapore from which experience will be gained in the use of Grid technology to support research in the context of an ‘extended enterprise’. In addition to these high-level objectives, the project also looks to develop Grid-enabled capability and products for use by the wider community. This paper reports on the current status of the GECEM project and discusses a prototype Grid integrating resources at the BAE Systems Advanced Technology Centre near Bristol, the Welsh e-Science Centre (WeSC) in Cardiff, and the University of Wales, Swansea (UWS). This Grid is capable of taking a model geometry generated at BAE Systems, transferring it to UWS where it is meshed. The meshed geometry is then transferred to WeSC where it is used to solve a computational electromagnetics problem and visualised.*

*Keywords:* Computational electromagnetics, Grid, extended enterprise, mesh generation.

## 1 Introduction

Computational electromagnetics (CEM) is of increasing importance to the civil and defence sectors. It is central to important problems such as predicting the electromagnetic compatibility between complex electronic systems, and the response of systems to lightning strikes and electromagnetic pulses. These issues are of key concern in possible future platforms such as the More Electric Aircraft (MEA) and the All Electric Ship (AES). In the MEA, hydraulic-mechanical systems are replaced by electro-mechanical or electro-hydrostatic systems allowing the engines to be used solely for thrust and electrical power rather than for maintaining hydraulic pressure. These concepts are influencing the design of the Airbus A380 super-jumbo. In the AES, the use of electronic systems has the prospect of improving operating efficiency and issues of in-life support.

Large-scale CEM simulations are computationally intensive, and can involve access to resources that are intrinsically distributed. For example, in the case of an “extended enterprise” in which multiple partners from industry and academia are cooperating to design and build a complex system that requires CEM simulations, the geometry of a component may be created at one location, a mesh conforming to this geometry may be generated at a second location, and a CEM simulation based on the mesh may be performed at a third location. Finally, the output from the simulation may be analysed and visualised at one or more other locations. In such a situation, the partners in the extended enterprise are prepared to share data (the geometry, the mesh, the simulation output), but not the often proprietary software systems and the hardware that generate the data (the mesh

generator and CEM solver code). Thus, it is not feasible to place all the data, compute, and human resources in one geographical location. The Grid, therefore, is an excellent candidate for providing the infrastructure needed to support extended enterprises. It should be noted that “extended enterprise” has essentially the same meaning as “virtual organisation” [1].

This paper reports on the current status of the Grid-Enabled Computational Electromagnetics (GECEM) project and discusses a prototype Grid integrating resources at the BAE Systems Advanced Technology Centre near Bristol, the Welsh e-Science Centre (WeSC) in Cardiff, and the University of Wales, Swansea (UWS). This Grid is capable of taking a model geometry generated at BAE Systems, transferring it to UWS where it is meshed. The meshed geometry is then transferred to WeSC where it is used to solve a computational electromagnetics problem and visualised. The next step in this work will be to extend the Grid to the project partners at the Singapore Institute of High Performance Computing, and to incorporate collaborative visualisation. The grid under development by BAE SYSTEMS for aerospace engineering is described elsewhere in these proceedings [2].

Important aspects of the research include the deployment and use of Grid-based mesh generation and manipulation services, the secure remote execution of computational electromagnetic simulations on the various hardware resources available at the Grid nodes including that of the Singapore Institute of High Performance Computing, and collaborative visualisation and analysis of both meshes and the simulation results by geographically dispersed participants.

A critical issue in GECEM, and in the use of the Grid in general, is the ability to make effective use of the distributed resources in the face of dynamically changing network bandwidth constraints. Hence there is a need to monitor Grid resources, including the

network, and make scheduling decisions that ensure good service in terms of both performance and fault tolerance.

Another issue that the GECEM project will be examining is how simulation codes can be migrated to remote computers and run in a secure way. The ultimate aim in this area is to ensure that code is protected against unauthorized access throughout migration and execution. Although cryptographic techniques exist for securely migrating code, there is currently no mechanism known for protecting a code from interference by privileged users on the remote machine. Achieving truly secure remote execution will probably require changes in computer architecture and/or chip design, and although this is beyond the scope of the GECEM project, techniques for mitigating risk within a trust model for the extended enterprise will be investigated.

The rest of this paper is arranged as follows. Section 2 gives an overview of the current prototype GECEM Grid connecting BAE Systems Advanced Technology Centre near Bristol, Cardiff University, and the University of Wales Swansea. In Section 3, an overview of the GECEM project is given. Sections 4 and 5 described the mesh generation and CEM solver software, respectively. Approaches to collaborative visualization are considered in Section 6. Section 7 discusses the main features of a portal through which users access GECEM software and hardware resources. Finally, Section 8 summarises what has been achieved so far in the GECEM project, and outlines the main areas of future work.

## **2 The GECEM Grid**

The grid used for the GECEM project combines resources located at the BAE Systems Advanced Technology Centre near Bristol, the Welsh e-Science Centre in Cardiff, and the University of Wales, Swansea. We eventually plan to add resources at the Singapore Institute of High Performance Computing. The grid currently

uses Globus Toolkit 2 (GT2) as the middleware to enable the resources at each site to be accessed in a secure and uniform manner.

For the GECEM project we decided that resources should use and accept certificates signed by the UK e-Science Certificate Authority (CA). This allows interoperation with other UK grids, and relieves the GECEM project from the time-consuming task of running its own CA. It also simplifies the granting of access to other researchers within the UK, who may already have these credentials.

The extent of a grid can be defined using several different criteria. One possibility is to define a grid's boundaries based on a *trust horizon*, where a common set of credentials potentially accepted by each resource defines the extent of the grid. This follows from the simplicity of accepting a new user or resource from inside this horizon relative to accepting those from outside it. Using this criterion the use of the UK e-Science CA makes the GECEM grid appear to be the same as the UK e-Science Grid.

A better definition of the extent of the GECEM Grid is the *awareness horizon*, created through the existence of a GIIS specifically for the GECEM project. The Globus GIIS (Grid Index Information Service) provides a central point at which users can discover the other services available in a Grid. Once a user has been granted access to the Grid, they simply need to be pointed to the GIIS in order to discover resources in the Grid. By limiting a GIIS to contain only GECEM resources, searches are simpler since there is no need for a set of additional attributes indicating which resources are "GECEM-enabled".

Using GT2, the addition of a new user to the GECEM Grid requires the creation of accounts on each resource and modification of the standard Globus access control file. At present, there is no means of applying to

the VO for access to all resources. Instead, the user must apply to each site for access.

We expect fairly quickly to move to an OGSA-based architecture, in which access to services can be enabled as a single operation with lower administrative overhead at each site. This will be possible since OGSA allows us to provide users with access to GECEM-specific services without creating individual user accounts as required by GT2. The flexibility of quickly modifying the middleware used by the project is one of the main benefits of creating a grid separate to the main UK e-Science Grid.

This is possible because a resource can provide services to multiple grids as long as the various specifications do not conflict. The resources at Cardiff University, for example, are available in both the GECEM and UK e-Science Grids, and the same machine hosts both the GECEM GIIS and the WeSC subtree of the UK e-Science GIIS without the grids being aware of each other.

### 3 GECEM Project Overview

The GECEM project will Grid-enable the essential aspects of industrially-relevant computational electromagnetics (CEM) using a service-oriented architecture based on emerging standards such as the Open Grid Services Architecture (OGSA). Services for mesh generation and processing, the migration of CEM codes to remote platforms, and collaborative visualisation and analysis form the basis of a globally distributed extended enterprise for which security and performance are key concerns. A typical mode of use would be the generation of a mesh using a meshing service at Swansea, the solution of a CEM problem on this mesh on a supercomputer in Singapore, and the collaborative visualisation of the results by participants at Cardiff University and BAE SYSTEMS in Bristol.

A web-accessible problem-solving environment (PSE) provides the main interface through which these services are accessed. This builds on previous work at Cardiff and Swansea on PSEs for scientific and engineering applications [3, 4]. The PSE will support the composition of applications from service-based components, the execution and monitoring of such applications on remote resources, and the collaborative visualisation, exploration, and analysis of the application results. The PSE maintains and provides access to an archive of results. In addition, the PSE also provides an interface to meshing services and supports the collaborative visualisation of meshes.

The meshing service will provide access to surface and volume mesh generators and a mesh generation toolbox for industrial problems to which partners can add their own tools. The toolbox will enable a user to build a mesh for general geometries. The meshing service will support the input of CAD data in the widely-used IGES format, as well as STEP and FLITE (the in-house format of BAE SYSTEMS) formats. Mesh analysis services will include validity checks and mesh quality statistics. Other features include a surface patch merger, a geometry builder, and facilities for geometry repair. The surface mesh generator will support triangulation and unstructured quadrilaterals, and the ability to mesh across boundaries and non-manifold geometries. The volume mesh generator will support tetrahedral, hexahedral, prismatic, and pyramidal meshes. Mesh optimisation and enhancement facilities will also be provided.

The ability to execute a simulation on a remote resource is important in a number of industrial settings, for example, when a company does not have the necessary computing power in-house. In such cases the simulation code could be installed on the remote machine that then serves as an Application Service Provider (ASP). However, this may not always be the best model for remote execution. A company

may not want to place a valuable or business-sensitive code on a third-party machine for an extended period of time because of the risk of unauthorised access. To minimise such risks a company may prefer to keep the code on their own machine and migrate it to the remote machine only when it is to be executed, after which it is deleted from the remote machine. This approach may also be appropriate when a code is in development and/or undergoing frequent changes. Services will be provided to support the secure migration, remote execution, and deletion of the application, and the secure return of the application results to the user. The transfer of code and data between machines can be handled securely by encryption, however, once the code is decrypted on the remote machine it is vulnerable. Although it is impossible to provide complete security in such cases, the proposed research will investigate mechanisms for secure remote execution, perhaps building on the *rexec* system developed by Chun and Culler at the University of Berkeley [5].

The collaborative visualisation and interpretation of complex 3-D meshes and scalar and vectors fields will be another major area of the GECEM project. To make effective use of visual cues, such as perspective and occlusion, immersive platforms will be used extensively. The collaborating partners, in general, will be globally distributed, use a heterogeneous set of visualisation platforms and software environments, and be subject to dynamic bandwidth constraints. Visualisation of large scale scientific data sets using the Grid and a heterogeneous visualisation environments (ranging from hand-held devices, to workstations, to semi-immersive flat-panel displays, and to fully immersive CAVEs) is an important aspect of the GECEM project.

#### **4 Mesh Generation Service**

GECEM uses a mesh generation service based on previous work done at UWS into

parallel mesh generation [6]. The approach adopted for parallel mesh generation is based upon a geometrical partitioning of the domain. The complete domain is divided into a set of smaller sub-domains and a mesh is generated independently in each sub-domain. The combination of the sub-domain meshes produces the mesh for the complete domain. A manager / worker model is employed in which the initial work is performed by the manager, before distributing the mesh generation tasks to the workers. The entire procedure can be divided into four separate stages:

1. Starting from a surface triangulation, the domain is partitioned using a geometrical partitioning scheme into  $N$  sub-domains.
2. The sub-domain boundaries are mapped into two dimensions and a 2D advancing front generator is employed to mesh the mapped surfaces. The triangulations of the inter-domain boundaries are mapped back to three dimensions.
3. A dynamic load balancing scheme is employed to generate meshes in each sub-domain. This scheme uses the fact that the proposed strategy involves no communication between processors so that more than one domain may be allocated, in turn, to each available processor. The number of domains given to each processor depends on the workload required for each sub-domain.
4. The mesh is post-processed, by node smoothing on inter-domain boundaries, and the inter-domain communication table is constructed.

The structure of the parallel grid generator is a single program multiple data (SPMD) model. Sub-domain boundary data has to be passed from the manager to worker processors and sub-domain meshes passed back to the manager. MPI is used as the message-passing library.

In future work the manager process will be wrapped as a Web service. It will receive geometry data as input and return the corresponding computational mesh.

## 5 CEM Solver Service

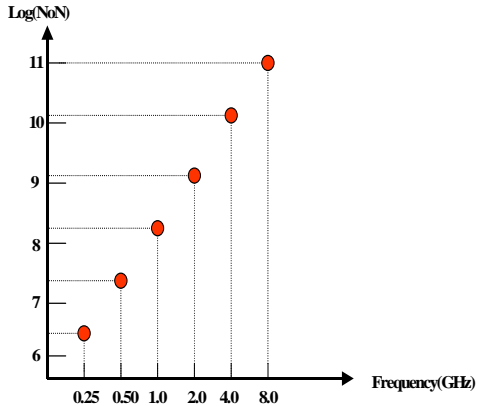
Due to the compute-intensive nature of large-scale CEM simulations the CEM solver service used by GECEM is based on a parallel solver developed at UWS for electromagnetic scattering simulations. Solvers for other types of CEM problem will be added in the future.

The simulation of electromagnetic scattering of realistic frequencies invariably requires the use of extremely large meshes. Figure 1 shows how the typical mesh size varies with frequency when considering a simulation over a complete aircraft. Such simulations require the use of significant computational resources and, in this case, the use of parallel computers becomes essential.

The solution algorithm employs an explicit finite element procedure for the solution of Maxwell's curl equations in the time domain using unstructured tetrahedral meshes [7]. An absorbing perfectly-matched layer (PML) is added at the artificial far field boundary that is created by the truncation of the physical domain prior to the numerical solution.

The computation of the radar cross-section (RCS) requires the evaluation of an integral over a closed surface enclosing the scatterer for each viewing angle. In the present implementation of the RCS solver, the surface is taken to be the surface of the scatterer and, consequently, only information on this surface is required. Furthermore, the computation of the RCS for one viewing angle is independent of the computation for any other viewing angle, so that the RCS computation can also be parallelised in the following manner:

1. Discard the volume mesh and recombine the surface mesh data into a global surface mesh.
2. Communicate the recombined global surface mesh to each processor.
3. The number of viewing angles required is then divided equally between the available processors.



**Figure 1: Typical Mesh Sizes for CEM Computations**

## 6 Collaborative Visualisation

GECEM will support the collaborative visualization of meshes and electromagnetic fields. The Resource-Aware Visualisation Environment (RAVE) project at WeSC [8] and the Visualisation in Parallel (ViPar) project at UWS [9] will provide input to the development of this service, as will also related projects elsewhere, such as gViz. The gViz project is extending IRIS Explorer and its collaborative tools to work in a Grid environment, and will develop a fully Grid-enabled extension of IRIS Explorer, to allow an e-scientist to run Grid applications through the IRIS Explorer user interface [10].

RAVE is a collaborative visualization environment that scales from immersive platforms, such as CAVEs and ImmersaDesks, to non-immersive PCs and workstations, and even to PDAs or any other

network-enabled display. Because of the diverse capabilities of the display platforms the environment will be 'resource-aware' in the sense that the platform where the rendering is done and the graphical representation sent to a display client will be determined by factors such as the capabilities of the client and the network bandwidth.

ViPar is a problem-solving environment that enables a user to perform unstructured grid generation in parallel, to execute computational fluid dynamics and CEM solvers on parallel platforms, and to perform the visualisation of grid data and solution in parallel. ViPar allows the user to visualise large geometry and mesh data sets and perform any necessary interaction tasks in order to define inputs to the other modules such as mesh sources and boundary conditions, and perform any mesh quality analysis and solution post-processing operations. In ViPar, mesh generation and CEM computations are done on a parallel computer, and the rendering is done on a client graphics workstation. The large volume data sets are stored and traversed on the parallel server with only the geometric primitives that are to be actually rendered being transmitted to the workstation.

It is anticipated that two types of collaborative visualization will be support in GECEM. In the first, one participant will be designated as the leader and will be able to navigate the data by selecting the viewpoint, lighting conditions, and other related attributes. In this mode all participants will see the same scene as the leader, and will be able to interact via audio links. In the second approach each participant will be able to navigate the data independently. The idea here is that when a participant discovers something of interest, other participants can subscribe to that participants view. In effect, this forms a sub-group of participants with a leader, as in the first mode.

## 7 GECEM Portal

User access to all GECEM software and hardware resources will be via an application portal, or problem-solving environment. This portal will hide the complexity of the Grid system from the end-user. The main functions of the GECEM portal are as follows:

1. To maintain an archive of GECEM-compatible geometries generated by third-party software.
2. To maintain an archive of CEM simulation results and related metadata.
3. To provide an environment for graphically composing applications. Typically this will involve selecting geometry data that is passed to the mesh generator. The resulting mesh is then passed to a selected CEM solver and the output is stored in the archive of CEM simulation results for later analysis and visualization.
4. To provide access to a Grid execution environment to which GECEM applications can be submitted. This execution environment is responsible for scheduling the application and returning the results to the portal.
5. To support the collaborative analysis and visualization of results stored in the CEM simulation archive.

The GECEM portal is currently being designed, and it is intended to build on portlet aggregation techniques by making use of Apache JetSpeed. This is the approach recommended by the Grid Computing Environments Research Group of the GGF.

## 8 Summary and Future Work

The GECEM project is still in the early stages of development. However, a simple prototype of the GECEM Grid described in

this paper has been implemented and demonstrated. This grid connects BAE SYSTEMS, WeSC, and UWS, and can be used to perform distributed CEM simulations in which geometry data resides at one site, and the mesh generation, CEM simulation, and visualization of output, are performed at other sites. Currently these tasks, and the flow of data between them, are controlled by hand-written scripts, but the aim is to generate these scripts automatically within the GECEM portal, based on the graphical composition of CEM applications by users.

Future work will focus on the following key areas:

1. Developing the GECEM Grid and incorporating resources at the Singapore Institute of High Performance Computing into it. The current GECEM Grid is based on GT2, however, we intend to move swiftly to a GT3-based grid. Key tasks in this migration will be representation of the mesh generator and CEM simulation solver(s) as OSGA-compliant services that interact via some messaging service, such as NaradaBrokering [12]. This area also included secure remote execution and scheduling.
2. Developing the GECEM portal as outlined in Section 7.
3. Developing support for collaborative analysis and visualization. The initial effort here will go into post-simulation examination and navigation of the results, but the ability to interactively steer a simulation without interrupting its execution is also of interest.

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