Medical Simulation Services via the Grid

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Abstract. As the Internet revolutionised access to information, the Grid will revolutionise access to computer applications and software systems. In general, this includes the highly important aspect of access to information resources such as Grid database systems (data-driven Grid applications), but we concentrate here on computational services providing numerical simulations for analysis, prediction and virtual prototyping to the medical sector ("bio-numerics"). The aims and objectives of the European Commission project GEMSS [1] will be presented and a description of the potential impact of the bio-numerics applications through examples from previous or ongoing European projects involving GEMSS partners, such as SimBio, COPHIT and BloodSim.

Keywords: Computational Grid, medical simulation services, Grid security, bio-numerics, high-performance computing

1 Introduction

This paper discusses two main questions:

– How can bio-numerical simulation help clinical practitioners?
– How can bio-numerical simulation services be brought into clinical practice?

Answers to the first question are provided by numerous results from research groups all over the world. In Section 2, we present examples from previous or still ongoing European projects involving GEMSS partners, such as SimBio [2], COPHIT [3] and BloodSim [4].

Often, however, such efforts have a very limited clinical impact, because there is no convenient or practical way for the typical potential medical end user to access the necessary software and hardware resources. Tackling this problem is the core task of GEMSS (Grid Enabled Medical Simulation Services), an EU IST project lasting 30 month, which commenced in September 2002. It will demonstrate how Grid technologies can be used to enhance healthcare by bringing a variety of medical computing and resource services into the user's environment. GEMSS will create an innovative Grid middleware that can be used to provide medical practitioners and researchers with access to advanced simulation and image processing services for improved pre-operative planning and near real-time surgical support. The Grid will also allow computational resources to be brought to the medical technology industry, already using bio-numerics for virtual prototyping, but requiring larger-scale compute resources due to the growth in the complexity of design problems made tractable by numerical methodology advances.

GEMSS will build the services and environment middleware on top of existing Grid and Web technologies, maintaining compliance with standards thereby ensuring future extensibility and interoperability. The project will create a test-bed to evaluate and validate the GEMSS environment, including its integration into the end-users working environments. The test bed will provide support for sophisticated authorisation, workflow, security, error detection and recovery. Furthermore, GEMSS aims to anticipate privacy, security and other legal concerns by examining and incorporating into its Grid services the latest laws and EU regulations related to providing medical services over the Internet.

The rest of this paper is organized as follows: In section 2, we show how numerical simulation has been successfully used to enhance medical practice, building on experience of GEMSS users from previous projects. Section 3 deals with a general overview on how the Grid may bring numerical simulation services to medical end users. Section 4 presents the approach the GEMSS projects takes provide Grid-enable medical simulation services, and gives an overview on the target services which will be provided by GEMSS. Finally, we conclude with a short outlook.

2 Medical uses for bio-numerical simulation

Biological modelling spans a huge range of time- and length-scales, starting from classical bio-informatics, genomics and proteomics, over cell modelling to the simulation of single anatomical structures and whole organisms. Interaction and coupling between models of different scales is still largely out of reach.

When dealing with bio-numerical simulation, it is necessary to distinguish between *generic* simulation for fundamental research, and simulation *specific* to a given individual. It is the latter case which typically is important in a clinical context. Here, in addition to overall modelling problems, the efficient and robust acquisition and processing of individual patient body data becomes a key factor of success.

In the SimBio project, a key innovation is the use of actual scan data from individual patients for modelling and simulation in order to improve clinical practice. The three pilot applications of SimBio are head mechanics as a prerequisite for maxillo-facial surgery planning, which is taken up in the GEMSS project and discussed in Section 4.3, electromagnetic source localization in the brain, and knee mechanics for prosthesis design.

2.1 Electromagnetic source localisation

A common clinical task in neurology and neuropsychology is to find realistic electromagnetic source distributions in the human brain, for instance for curing epilepsy. This search is based on EEG measurements that yield electric potentials on the surface of the head. The data analysis is a so-called inverse problem; it requires in a first step the repeated (up to 10,000 times) solution of the corresponding forward problem, involving using FEM for solving field problems with more then 1 million unknowns. Thus, source localization is best run in a HPC environment. In SimBio, the parallel code NeuroFEM [5] is used to solve the forward problem. An inverse toolbox then solves the inverse problem, using the results of the forward problems (see Fig. 1 for a low resolution example).

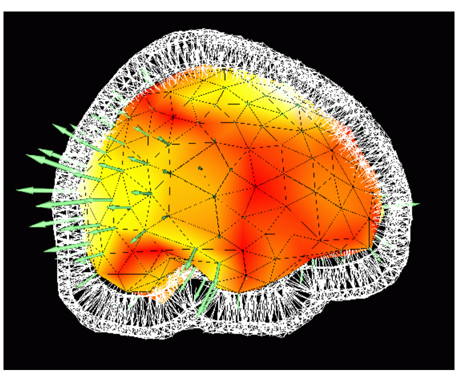

Fig. 1. Source localization in the brain: Electric field visualization

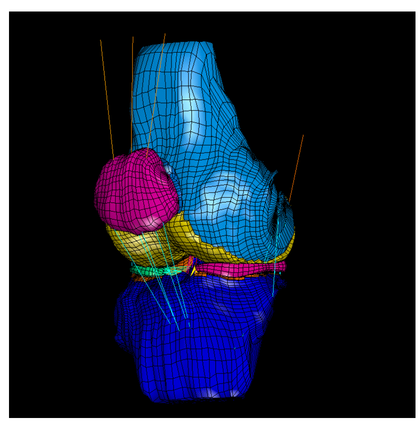

Fig. 2. Full knee model created by a template mapping approach

2.2 Knee mechanics simulation

The knee joint is the largest joint in the body. Its healthy functioning is essential for an individual's capacity to walk and perform activities of daily living. The menisci perform important roles in force transmission across the knee joint carrying between 40-70% of load, shock absorption, stability (improving joint congruence) and lubrication. If the meniscus is too badly damaged, an implant might become a viable option. Therefore, the mechanics of individual patients' knees will have to be simulated. This implies takings MR images of a patient's knee, fitting additional structures like ligatures not visible on the MRI by using a template [6], generating a smooth surface mesh of the bones and a volume mesh of the meniscus, and simulating the mixed-dimensional contact problem (see Fig. 2 for a full model). The latter is solved using ESI's PAM-SAFE software. This approach will enable virtual prototyping of test designs for a meniscal implant to improve the potential for a successful implant development for menisci.

3 The Grid as a platform for providing medical simulation services

The Grid probably is one of the currently most actively developing concepts in the IT community. Depending on the individual point of views, it may mean rather different things to different people. Our working definition of a Grid is the following:

> A Grid is an internet-enabled, distributed system linking computational, data repository and data production resources to enable (real or virtual) organizations with geographically dispersed facilities to more efficiently use their resources.

A very well-known variant of the Grid, the so-called *data grid*, is e.g. developed in the European Data Grid project [7]. Its main target applications are to master the huge amount of data output expected from the Large Hadron Collider being built at CERN, to provide access to genomics and medical image data bases, and to handle satellite image streams. Here, we focus on *Grid computing*, which is another, very important aspect of Grid. It means to

- provide computational resources across wide area networks
- provide computational services on these resources
- possibly combining computational resources to overcome time or space limitations of single HPC systems (an approach whose feasibility crucially depends on the nature of the concrete computations at hand). This approach links to the concepts of meta-computing or data-farming.

The potential of Grid computing makes it a good candidate for bringing high-performance simulation services, such as described before and in Section 4.3, to medical practice. In a Grid-based scenario, a medical end-user would have installed locally some sort of user interface, probably a control GUI and some visualization tool for images and/or geometric models, plus some grid-enabled client software managing the interaction with the remote services. On the server side, a corresponding counterpart handles the client's requests, and forwards them to typically high-performance, compute-intensive applications, which themselves might be dispersed over a wide range of HPC hardware.

This approach brings the following benefits to medical end users:

- They are provided with advanced tools at their workplace through easy-to-use interfaces
- They do not need to acquire IT or engineering specialist know-how
- Their institute does not have to invest in HPC hardware and the related IT support personnel
- They will pay only for the services actually used, and not for an expensive specialized piece of software they use only a few times
- The reliable, pervasive and interoperable Grid infrastructure can accommodate new services and updates to existing ones as they become available

Obviously, before this scenario becomes common practice, a number of scientific, technical, social and legal problems have to be solved. Paving the road toward making this vision a reality is the goal of the GEMSS project.

4 The GEMSS project - Grid Enabled Medical Simulation Services

The GEMSS project consortium consists of ten partners from academia and industry, and heavily builds on the partners' experience gained from previous research projects in the field, like SimBio, BloodSim, COPHIT, and GRIA [8].

4.1 Project Objectives

GEMSS aims to bridge the current gap between medical practice and state-of-the-art medical simulation applications. Unlike a number of purely technology-centric approaches, GEMSS considers also legal aspects of Grid computing the medical field, in order to address corresponding obstacles at an early stage. In detail, its objectives are

– Demonstrate that the Grid can improve pre-operative planning and near- real-time surgical support by providing access to advanced simulation and image-processing services
– Build middleware on existing or developing Grid technology standards to provide support for authorisation, workflow, security and Quality of Service aspects
– Develop, evaluate and validate a test-bed for the GEMSS system, including its deployment in the end-user's working environment
– Anticipate privacy, security and other legal concerns by examining and incorporating into its Grid services the latest laws and EU regulations related to providing medical services over the Internet.

4.2 Security and legal issues in GEMSS

Since GEMSS is concerned with the processing of highly confidential and private information, such as images of patient heads and commercially sensitive fluid dynamic models, utilizing best practice security is crucial; indeed this has been identified as one of the major legal requirements to operate within current EU and national law. The GEMSS Grid infrastructure will employ commercial off the shelf (COTS) technology such as a public key infrastructure (PKI) supporting ITEF X.509 standards. Such security technologies will be evaluated with respect to the GEMSS Grid, in addition to the creation of a methodology for assessing the security needs at each GEMSS partner's site. European law will also be reviewed, and any significant legal obstacles to the development of an EU Grid identified. Both the legal work and security work will directly feed into the GEMSS design as the project progresses.

4.3 Medical Services provided in GEMSS

GEMSS comprises in total six different medical simulation service scenarios, in order to cover a sufficiently broad spectrum of medical applications. These application all involve at least some of the following generic steps:

1. Data acquisition (CT, MRI, SPECT images, or image data bases)
2. Digital model preparation (image pre-processing, segmentation, registration, meshing)
3. Mesh processing (quality checking, topological checking, boundary conditions for simulation)
4. Simulation (FEM, CFD)
5. Visualisation, analysis, result reporting

All these components have to be Grid-enabled, i.e. interfaced to a Grid toolkit. Some of these applications might run on the client's side, some will need a HPC environment.

Fig. 3. General setup for maxillo-facial surgery

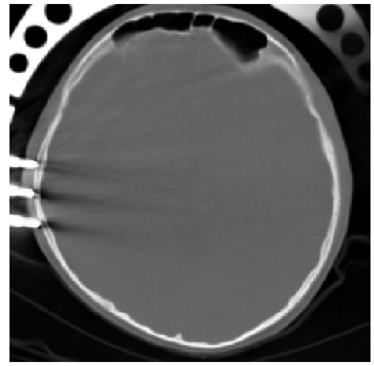

Fig. 4. CT slice showing skull and halo screws

Maxillo-facial Surgery Planning In clinical practice treatment of patients with in-born deformations of the mid-face is performed by cutting ill-formed bones and pulling them into the 'right' position. In order to do so, a halo frame is mounted to the patient's skull (see Fig. 3). Distractors, mounted to the halo fixed at certain points in the midface, exert a force on a midface region, gently pulling it to a pre-defined position in order to achieve a medically and cosmetically pleasing result. To achieve an optimal intervention result, pre-operative planning is crucial and has to be repeated for each patient due to the individual specifics of the in-born deformation. Based on experience gained in SimBio [9], it was found that simulations have to be based on highly resolved meshes in order to represent the complex midface structures with sufficient detail, resulting in meshes with more than one million cells (see Fig. 6), so the forward FEM models must be computed on HPC platforms with sufficient compute power and also memory. Pre-operative planning involves "playing" with different what-if scenarios, a first step includes positioning the halo (cf. Fig. 5). Thus, user defined (fast) response times are highly desirable in order to provide tools that are accepted in a clinical planning environment. Specific target users are medical practitioners in the area of maxillo-facial surgery who can use an interactive virtual environment for their planning.

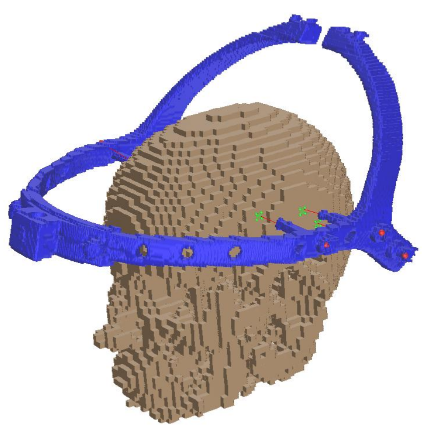

Fig. 5. Virtual halo placement tool

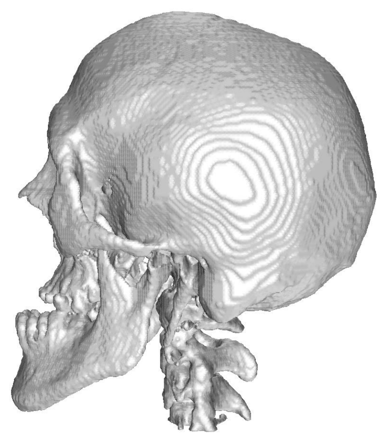

Fig. 6. Mesh of skull using volumetric marching tetrahedra

Quasi-realtime Neuro-surgery Support by Nonlinear Image Registration The major shortcoming of image-guided neuro-surgical planning based on pre-surgically acquired functional MRI (fMRI) data is the brain shift phenomenon. The occurrence of surgically induced deformations invalidates positional information about functionally relevant areas. This problem can be addressed by non-linear registration of pre-operative fMR images to intra-operative MRI [10] acquired by an Open-MR scanner, or to intra-operative 3D ultrasound data (see Fig. 7 for deformation fields calculated by nonlinear registration). In order to achieve response times adequate for surgical practice (less than 10 minutes), the GEMSS testbed will allow to employ remote high-performance hardware.

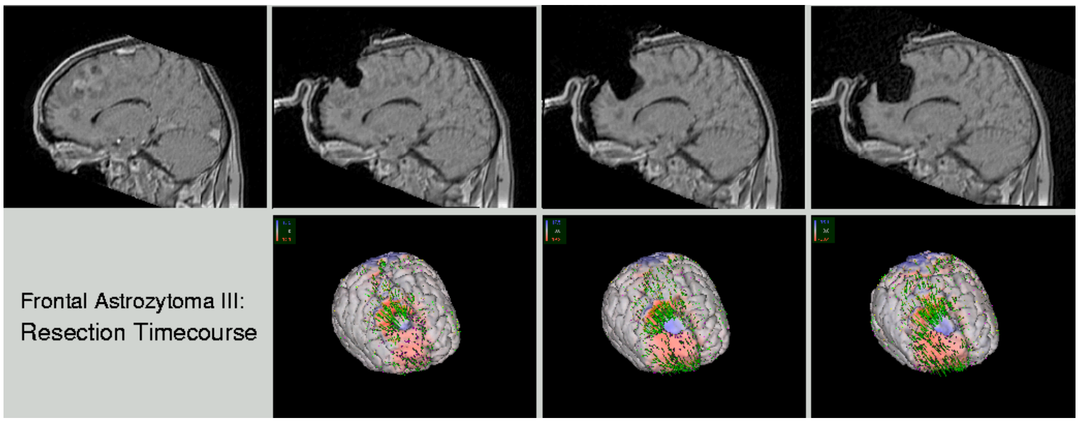

Fig. 7. Brain deformations due to tumor growth

Near Realtime Cranial Radio-surgery Simulation Radiosurgery is an important neurosurgical treatment for a variety of neurological conditions, including cancer. The need for accurate focusing of radiation to the treatment site requires a combination of stereotactic localisation of the patient relative to the treatment system (achieved with a frame attached to the skull) and accurate modelling of the radiation dose distribution within the head. Using the stereotactic frame, image data registered to the treatment space allows delineation of the lesion. Image data also provides information relevant to radiation attenuation and scatter within the patient, which in turn provides data for calculation of the radiation dose distribution within the head. The most accurate distributions are obtained using complex, compute intense Monte-Carlo computer simulations, see Figure 8. However, because of the need to treat patients as soon as possible after the stereotactic frame is fitted, rapid computations of these distributions are needed. The use of an efficient parallel Monte-Carlo code will allow fast response on suitable HPC platforms. This will enable high accuracy treatments to be planned and executed within the existing time constraints.

Inhaled Drug Delivery Simulation Respiratory delivery of medication (cf. Fig. 9) is fraught with difficulties, since one of the primary functions of the respiratory system is the removal of contaminants — medical or otherwise — from the air being breathed by an individual. Numerous mechanisms within the lung make it very effective in this role and it is widely accepted that the majority of medicament introduced by a therapeutic inhalation device rarely reaches the alveolar target it was designed for. However, when armed with detailed knowledge of airway geometry and flow, it is possible to deliver a medicament to any desired region of the lung, provided that particular timing and particle size constraints are met. A simulation can be used to optimize delivery of inhaled therapies to the lung. COPHIT [3] is composed of 1D and 3D compartmental models, representing the complete delivery process, from the medical device containing the agent, through

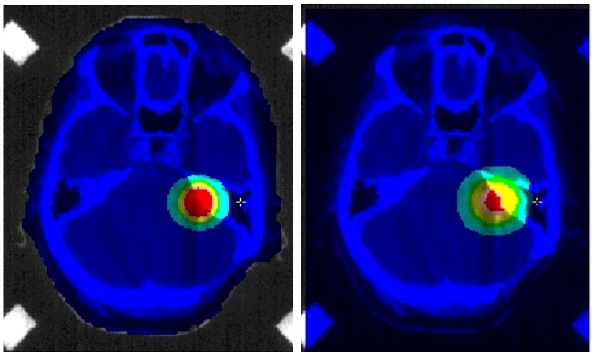

Fig. 8. Radio-surgery planning: Conventional (left), and improved Monte-Carlo (right) computed dose distributions

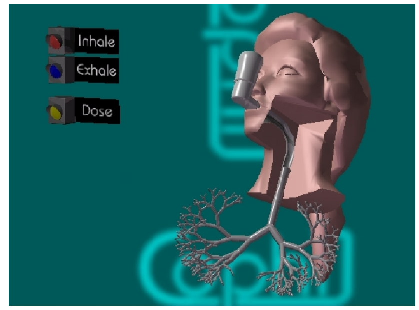

Fig. 9. Inhaled drug delivery setup (COPHIT)

any aerosolisation and entrainment into the gas stream, down the bronchial tree (determined from radiological data) and ultimately across the alveolar membrane into the pulmonary arterial circulation. The computationally most demanding part is the 3D CFD simulation. A Grid based approach will allow e.g. a SME consultant to use high-performance computing to provide design solutions for inhalation devices according to client needs.

Compartmental Modelling Approach for the Cardiovascular System Simulation of the cardiovascular system is already a valuable tool in the development of prostheses. Its role in surgical planning will develop as run times reduce and studies validated against in vivo data are presented in the clinical literature. An exciting application of this development will be the facility to answer 'what if' questions in the context of an individual patient. It is anticipated that the Grid will provide access to the necessary computing power. For instance, analysis of the haemodynamics of cardiovascular devices such as prosthetic heart valves (see Fig. 10) is now routinely used as part of the development process. Additionally, structural finite element analyses can also support the design process. The quality of the outcome can be improved by the use of sophisticated fluid-solid simulations which recognise the complex interplay of the fluid and structural elements of the system. Tools such as this require considerable computing power and GEMSS is an opportunity to evaluate their efficacy in a clinical setting.

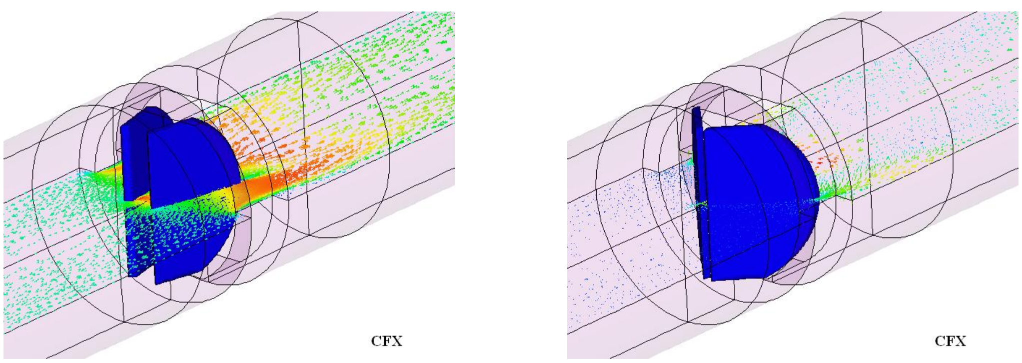

Fig. 10. Simulated flow through a St. Jude heart valve (BloodSim project [4])

Advanced Image Reconstruction Single photon emission computed tomography (SPECT) is a cost effective and robust method for diagnosis of cancer, heart diseases and functional pathologies of the human body. The visualisation of the distribution of radio-pharmaceuticals provides valuable complementary information to the representation of anatomy from high-resolution imaging modalities as x-ray CT and magnetic resonance imaging. Conventional reconstruction algorithms used in clinical practice, e.g. filtered back projection, generate images representing trans-axial 2D slices of the object. All information outside the assigned area is neglected in the reconstruction process. Modern fully 3D iterative reconstruction algorithms provide very accurate image reconstruction for the whole image volume, by considering principal 3D effects of data acquisition, as photon scatter and collimator geometry. In addition, with a priori information about photon attenuation, e.g. from simultaneous measurements of attenuation coefficients or assessment from co-registered CT scans, iterative reconstruction methods allow the accurate correction of non-uniform attenuation. The correction of attenuation artifacts is of particular interest in the visualisation of myocardial perfusion and in tumour staging. However the need of high computational resources restricts the use of fully 3D reconstruction algorithms to dedicated research centres. Grid technology will enable the use of advanced 3D image reconstruction software for improved healthcare within a clinical environment by relying on transparent access to remote parallel computing hardware.

5 Conclusions

Grid technology has potential for enormously enhancing the computing infrastructure and providing enhanced computational services to new user communities.

The simulation services included within the GEMSS project will demonstrate potential impact on specific medical areas, aiming to improve: non-invasive diagnosis and pre-operative planning, operative procedures, therapeutic protocols, design, analysis and testing of biomedical devices, such as heart valves, and inhalers.

Modelling of individuals is an ongoing research topic and targets the complete simulation of the human body — there is a great deal still to be understood and developed. Grid computing hopefully can bring those developments to the medical user community.

If we risk a look beyond the current state-of-the-art, multi-scale modelling and simulation to understand, predict and design or control (for medical treatment) the interactions between effects at the disparate length-scales come to mind. Yet, a simulation "from molecules to man" will certainly remain a vision for many years to come.

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