Head-mechanical simulations with SimBio

By Jochen FINGBERG, Guntram BERTI, Ulrich HARTMANN, Achim BASERMANN

ABSTRACT

The SimBio project provides a generic simulation environment for advanced clinical practice and health care. A key feature is the input of individual patient data to the modelling and simulation process. The project evaluation & validation will demonstrate improvements in non-invasive diagnosis, pre-operative planning and design of prostheses. The SimBio environment components are: discrete representation of the physical problem; numerical solution system; inverse problem and optimisation; visualisation. The environment will be designed for execution on parallel and distributed computing systems. The compute-intensive components of SimBio’s numerical solution system will be implemented on High Performance Computing (HPC) platforms. This paper is focused on an object-oriented approach to parallel non-linear Finite Element simulations which is implemented in the HeadFEM code. HeadFEM is a SimBio simulation component designed for the pre-operative planning of maxillo-facial surgery.

KEYWORDS bio-medical, simulation, Finite Elements, distributed computing, HPC platforms.

1. INTRODUCTION

The objective of the SimBio project, financed by the European Commission’s Information Societies Technology (IST) programme¹, is the improvement of clinical and medical practices by the use of numerical simulation. This goal is achieved by developing a generic simulation environment that enables users to develop application specific tools for many medical areas. The potential impact is demonstrated for specific areas through the SimBio evaluation & validation applications: electromagnetic source localisation in the brain, analysis of time-series data, maxillo-facial mechanics, knee-mechanics and prosthesis design. A key feature in the SimBio project is the possibility to use individual patient data as input to the modelling and simulation process - in contrast to simulation based on generic computational models. In order to meet the computational demands of the SimBio applications, the compute-intensive components are implemented on High Performance Computing (HPC) platforms. In addition to combining medical imaging and finite element analyses with HPC technology, the whole environment is integrated using Corba to allow remote-site computing, thus creating an internet-based clinical and medical support tool.

2. Bio-mechanical simulation with HeadFEM to support facial surgery planning.

One of the target applications of the SimBio framework deals with pre-surgical studies in the field of head biomechanics [2]. In particular, this refers to the modelling of the deformations emerging during and/or induced by surgical interventions. Thus, simulation supports the optimisation of operation procedures and the planning of therapeutic strategies. Currently, a study is underway to investigate the mechanical consequences of the forces that occur during the sequence of interventions to remedy inborn deformations of the human face (mainly cleft lip and palate, see Figure 1a and 1b).

Figure 1: (a) Pre- and (b) post-surgical situation.

In order to adjust deformed parts of the mid-face a metal frame (a so-called halo device, see Figure 2) is tightly fixed to the head using screws. After cutting the mid-facial bone along exactly defined lines, this device exerts forces on the bone structure to be relocated. The distraction path length governed by the externally applied forces amounts to a length of 10-30 mm at a rate of approximately 1 mm per day, depending on the application site and duration, which is typically in the order of a few weeks.

¹ “SimBio – a generic environment for bio-numerical simulation”, project number IST-1999-10378, is a 3-year project which commenced in April, 2000.
For the set-up of the computer model the tools described in the following chapters have been applied.

3. The Software Environment

The SimBio environment includes a complete chain of tools necessary for the entire process from geometric model generation from scan data (segmentation, mesh generation and mesh manipulation) to computer simulation and visualisation. Computed tomography (CT) and magnetic resonance imaging (MRI) provide a 3-dimensional description of internal structures by non-invasive measurements. The resulting image allows to distinguish different types of tissues.

3.1 Segmentation

After format conversion and selection of relevant slices from the raw data the first step is the identification of anatomical structures of interest in 3D volume element (voxel) datasets derived from medical scan data (CT or MRI). General segmentation involves the definition of anatomical structures by borders corresponding to signal intensity transitions at tissue interfaces. Here we use an intensity based algorithm (AFCM, adaptive fuzzy C-means algorithm [4]) which is able to simultaneously correct intensity inhomogeneities and provide good quality segmentations for structures of the human head. However, finding a generally applicable and fully automatic procedure is still an unresolved problem.

3.2 Mesh Generation

Next to this image processing step follows the geometric modelling of the structures identified in the previous step. The important difference to standard engineering problems is the lack of a continuum (CAD) geometry. The starting point is a discrete voxel dataset with a typical resolution of 1 mm. The VGrid algorithm [1] is based on an adaptive OCTREE data structure exploiting the Cartesian grid structure inherent in medical scan data. VGrid allows the fast generation of uniform and non-uniform (adaptive) tetrahedral and hexahedral meshes suitable for Finite Element simulations. A VGrid mesh of a caudate nucleus obtained with the original marching tetrahedral method and one with additional smoothing are depicted as wire-frames in Figure 4.

3.3 Mesh Tools

The scan data provide only information about geometry. The computer model is incomplete without initial and boundary conditions.

We have implemented special tools to apply forces
and set constraints in a user friendly way especially for large models such as the halo positioning tool shown in Figure 5. Additionally a module to analyse the quality of the resulting mesh elements was developed following an approach described in [7].

3.4 Specialised Finite Element Analysis with HeadFEM

HeadFEM is a SimBio simulation component designed for the pre-operative planning of maxillo-facial surgery. HeadFEM is a fully parallel computer programme for the solution of non-linear, finite deformation, large strain finite element problems employing neo-Hookean hyperelastic compressible and incompressible (for soft tissue modelling) constitutive equations. In HeadFEM the solution to the non-linear equations is achieved using the non-linear Newton-Raphson iterative method. The computer programme is implemented in C++ in a modular and object oriented way that simplifies maintenance and future extension of the code. The design of the HeadFEM module is based on the standard Finite Element Interface (FEI) definition from Sandia National Laboratories [5]. The FEI serves as an abstraction layer between finite element routines managing matrix-assembly and linear-solver modules. Thus, it insulates the finite-element application from "linear-algebra issues" such as sparse matrix storage formats and mappings from solution fields to distributed (in a parallel environment) equation numbers. The primary benefit is the provision of a standard interface to a variety of linear solver libraries.

Initially, HeadFEM uses a matrix interface of the FEI to link to the NEC PILUTS linear solver library, which comprises a variety of state of the art parallel iterative solution (CG, BiCGstab, symQMR) and preconditioning procedures ranging from simple diagonal scaling to incomplete Cholesky, threshold and distributed Schur complement methods.

For improved parallel efficiency a partitioning tool based on the DRAMA load-balancing library [6] is available.

The typical SimBio target platform for a finite element analysis with HeadFEM is a Linux PC-cluster as shown in Figure 6. With the recent arrival of an SX6i the use of a desk-side vector supercomputer will be investigated.

3.5 Visualisation

The simulation of bio-medical data often requires advanced - particularly accurate or of high resolution - visualisation tools and these are included in the visualisation component via both SimBio-internal tools and interfaces to external software [3].

4. Results

A 12 year old patient (Figure 1a and 1b) was scanned pre- and post-operation. Both CT datasets were registered by a fluid dynamic, non-rigid approach to solve the inverse bio-mechanical problem. As a result of the registration we obtained a displacement vector at each point of the pre-operative image representing the bone shift during the time interval. The spatial pattern of shape change is visualised as follows (see Figure 7): for each point on the surface, the displacement vector is decomposed into its normal and tangential components. Inward-pointing normal vectors are coded in red, outward-pointing in blue; colour intensity reflects the vector's magnitude. The scale is given in mm. The displacement vectors are shown as arrows.

Figure 6: NEC SX6i (top left) and NEC 64 CPU PC-cluster (right) installed at the C&C Research Laboratories in Sankt Augustin.

Figure 7: Visualisation of the geometric face change.
Skull deformations induced by the halo screws are calculated using an FE model of the head. The model was prepared by segmenting the initial CT image (see Figure 8 for an example including the halo) into three classes (background, skull, soft tissue) and meshing the labeled image with VGrid. The resulting forward problem was solved with our parallel finite element code that has been installed on the NEC PC-cluster. The equation system based on this mesh has about half a million unknowns and is solved by a preconditioned conjugate gradient solver from the NEC PILUTS library.

Figure 8: Slice of a CT dataset with halo and screws.

Figure 9 depicts the skull deformation caused by the screws of the surgical frame. Besides the expected focal inward deformation at screw positions, an outward protrusion of the skull at peripheral concentric areas is observed (see arrows). This result is in full agreement with clinical findings.

Figure 9: Calculated deformation of the skull (Red: inwards, blue: outwards).

5. CONCLUSION

The SimBio environment combines medical imaging and finite element techniques with up-to-date HPC algorithms and technologies. The SimBio project provides an extensive tool for numerical modeling of human body parts. A major advantage of the SimBio approach is the ability to set up models of body parts of individual human beings based on medical scan data. This concept thus paves the way for the future set-up of virtual models of individuals applicable for the investigation of a wide range of medical problems. The motivation is to improve the quality of health service that can be delivered to society by predictive computer simulations.

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REFERENCES

Jochen FINGBERG, Senior Principal Researcher, Technical Team Leader for Bio-Numerics and Bio-Informatics, obtained a PhD in Theoretical Physics from the University of Bielefeld in 1990 followed by postdoctoral positions in Computational Physics at the Supercomputing Centre in Jülich, at the Supercomputer Computations Research Institute in Tallahassee Florida, and at the University of Wuppertal. In 1997 he joined NEC’s C&C Research Laboratories in Sankt Augustin. Current research is focused on bio-mechanical simulations and the development of a parallel non-linear Finite Element code (HeadFEM). Recent contributions to EC projects were within the ESPRIT LTR project DRAMA and the IST project SimBio. Starting in September 2002 he will coordinate the recently approved EU project GEMSS (Grid-enabled Medical Simulation System).

Guntram BERTI, Research Scientist, obtained a MSc in mathematics at the University of Dortmund, and a PhD in mathematics at the University of Cottbus. Dr. Berti joined NEC’s C&C Research Laboratories in 2001. His current research is focused on bio-numerics, including mesh generation (VGrid mesh generator) and parallel FEM solver (HeadFEM code), and in developing generic mesh tools and algorithms (GrAL-Grid Algorithms Library). He contributes to the EU-funded projects SimBio and PRISM.

Achim BASERMANN, Principal Researcher, Technical Team Leader for Applications, Support Environments and Libraries, obtained a PhD in Electrical Engineering from RWTH Aachen in 1995 followed by a postdoctoral position in Computer Science at Research Centre Jülich GmbH, Central Institute of Applied Mathematics. In 1997 he joined NEC’s C&C Research Laboratories in Sankt Augustin. Current research is focused on parallel linear algebra algorithms, circuit simulation and financial applications. Contributions to EC projects were within the ESPRIT EC-DGIII Basic Research Project APPARC, the ESPRIT LTR project DRAMA, the ESPRIT project SEP-Tools, and the IST project SimBio. He further participated in the German BMBF (Ministry of Education, Science, Research and Technology) projects PARFEM and DYNA3D.

Ulrich HARTMANN studied physics in Heidelberg and Göttingen. The main focus of his studies lay on medical physics in the area of SPECT imaging. After having received his diploma in 1995 he started his PhD in Leipzig at the Max-Planck-Institute for Cognitive Neuro-science working in the field of finite element modelling for neurological problems. In 1998 he took the position as a research staff member at the NEC C&C Research Laboratories in St. Augustin. Here, he continued his work on finite element models in medicine and started working on the European project SimBio. In 2001 he became professor of medical engineering and informatics at the University of Applied Sciences Remagen where he is responsible for the biomechanics laboratory.