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Direct medical image-based Finite Element modelling for patient-specific simulation of future implants

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ABSTRACT

In patient specific biomedical simulation, the numerical model is usually created after cumbersome, time consuming procedures which often require highly specialized human work and a great amount of man-hours to be carried out. In order to make numerical simulation available for medical practice, it is of primary importance to reduce the cost associated to these procedures by making them automatic. In this paper a method for the automatic creation of Finite Element (FE) models from medical images is presented. This method is based on the use of a hierarchical structure of nested Cartesian grids in which the medical image is immersed. An efficient *h*-adaptive procedure conforms the FE model to the image characteristics by refining the mesh on the basis of the distribution of elastic properties associated to the pixel values. As a result, a problem with a reasonable number of degrees of freedom is obtained, skipping the geometry creation stage. All the image information is taken into account during the calculation of the element stiffness matrix, therefore it is straightforward to include the material heterogeneity in the simulation. The proposed method is an adapted version of the Cartesian grid Finite Element Method (*cg*FEM) for the FE analysis of objects defined by images. *cg*FEM is an immersed boundary method that uses *h*-adaptive Cartesian meshes non-conforming to the boundary of the object to be analysed.
The proposed methodology, used together with the original geometry-based *cg*FEM, allows prosthesis geometries to be easily introduced in the model providing a useful tool for evaluating the effect of future implants in a preoperative framework. The potential of this kind of technology is presented by mean of an initial implementation in 2D and 3D for linear elasticity problems.

1. Introduction

Nowadays, the use of numerical models based on volumetric image data is widespread in biomechanics. Great efforts have been made to solve the elastic problem in a number of patient specific medical applications using the Finite Element Method (FEM), common in structural engineering. This is the case, for instance, of the prediction of bone fracture risk [1], and the evaluation of bone quality parameters for the detection of osteoporosis [2,3]. Preoperative implant simulation is a particularly promising use for patient-specific numerical models. This is fundamental for several applications such as studying the effect of positioning [4], predicting the long term prosthesis performance thanks to the recent advances in bone remodelling [5], designing customized implants taking advantage of optimization and 3D printing [6].

The most common procedures [7] to obtain numerical models from volumetric images can be broadly categorised into two groups: the *voxel-based* and *geometry-based* methods, both based on standard FEM. The former convert each voxel into an element of the FE mesh simplifying the modelling stage but typically providing problems with a high number of degrees of freedom, whereas the latter rely on modelling strategies, often hard to make automatic, to define geometrical domains from the image data which are then meshed as in standard FE. There are other aspects which can make one of the two methods more suitable than the other. For prosthesis analyses, for example, the *geometry-based* FE approach [8] is usually preferred because the assembly between the geometrical models can be performed with standard CAD tools. On the other hand, when a reliable relation between voxel values and elastic properties is available, as in the case of bone CT scan, it usually easier to take it into account using *voxel-based* methods due to the correspondence between elements and voxels. Doing the same with *geometry-based* meshes is more

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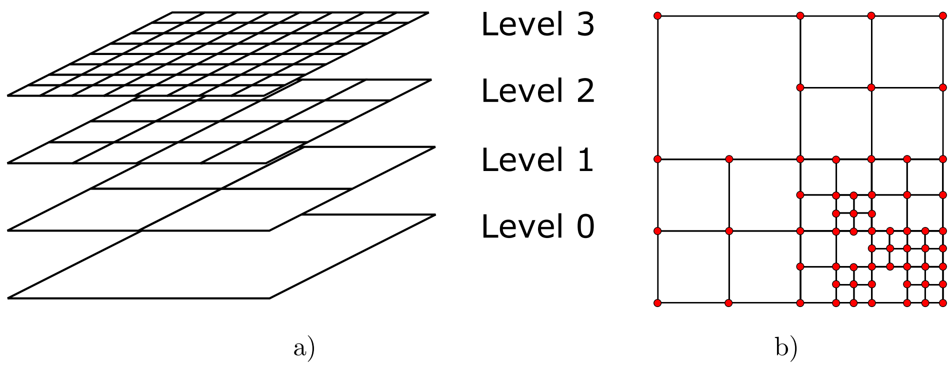

Fig. 1. *cg*FEM mesher. a) First levels of the hierarchical structure of nested Cartesian grids; b) Example of non-conforming Finite Element mesh with *cg*FEM.

complicated because the elements do not conform to the pixels. A possible solution lies in assigning each integration point the average value of the stiffness corresponding to the surrounding pixels. Nevertheless the size of this influence area is not univocally defined [9].

New methods have recently been proposed in order to reduce both human intervention and computational cost in patient specific simulations. Most of them are extensions of geometry independent techniques defined by the umbrella term of Finite Elements in ambient space [10] but available in the literature under a number of different names such as Fictitious Domain [11], or Embedded Methods [12], among others. These were originally developed to reduce the modelling effort for standard, CAD-based FE problems, which is, even in this case, responsible for about 80% of all the simulation time cost [13]. These methods simplify the mesh generation by using an auxiliary domain Ω_e, in general characterised by a simple, easy to mesh geometry, containing the problem domain Ω. The auxiliary, or meshing, domain Ω_e is discretised instead of the problem domain Ω. During the evaluation of the element integrals these methods require the information about the problem domain because the mesh does not conform to Ω. In particular we remark the application to image-based problems of X-FEM [14], Composite Finite Elements [15], or Finite Cell Method (FCM) [16].

We follow a similar path as the background of our proposal is the Cartesian grid Finite Element Method (*cg*FEM) [17], a method to solve CAD-based problems, which belongs to the family of the Finite Elements in ambient space. For the sake of clarity, we refer to it as *geometry-based cg*FEM in the following in order to distinguish it from the new method

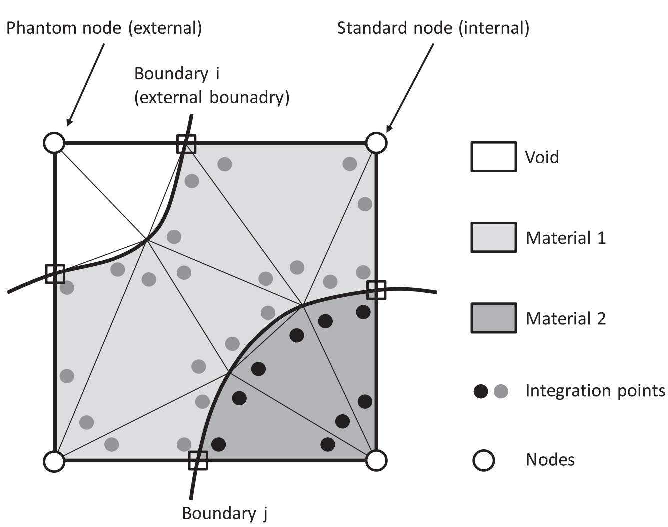

Fig. 2. Triangular integration subdomains of *cg*FEM element containing geometrical boundaries.

object of this paper which we call *image-based cg*FEM and address the problem of solving patient specific numerical models from volumetric image data. Finally, we call FEAVox the Matlab-based code which implements both *geometry-based* and *image-based cg*FEM. In both its versions, this has points in common with the family of Finite Elements in ambient space, especially with the Finite Cell Method (FCM).

FCM is a powerful method which combines the fictitious domain approach with high-order hierarchical Ansatz spaces. The results, in the initial formulation of the FCM, are enhanced by using *p*-adaptivity, *i.e.* by increasing the order of the shape functions used for interpolation, while the spatial discretisation is kept uniform. An octree structure of subcell is used for integration. These coincide with the voxels image-based models and on a hierarchical octree structure in CAD-based models.

In *geometry-based cg*FEM the problem domain is immersed into a hierarchical structure of Cartesian grids. For the elements on the boundary the stiffness matrix is calculated solely by integrating the area of the element actually lying within the domain Ω. Special techniques are used to account for the exact geometry during the element integration process thus avoiding modelling errors associated to an inexact representation of the boundary. A local *h*-adaptive refinement is used to enhance the solution.

In *image-based cg*FEM, we superpose a coarse Cartesian mesh upon the bitmap. As in the FCM, each element contains an heterogeneous distribution of elastic properties. As a consequence, the element stiffness matrix integration carries out a kind of material homogenization which makes it possible for *cg*FEM to keep the number of degrees of freedom (DOF) lower than in classical *voxel-based* methods. We use *h*-adaptivity to tailor the mesh to the bitmap on the basis of the evaluation of the pixel value distribution in each element. This is meant to prevent excessive material homogenization and the resulting loss of accuracy in the solution.

1.1. Objectives and paper structure

The main contributions of this paper are:

- to present a cheaper and more parallelizable integration procedure for $\mathbf{k}^e$ based on the least-squares recovery of the Young's modulus field in each element and compare it with other integration schemes;
- to study some limitations in the mesh size due to the use of pixmaps and propose a cost-effective mesh *h*-adaptive method;
- to propose a method to combine geometry and image-based *cg*FEM perform patient-specific simulations of implants.

The next section opens briefly reminding the main features of *geometry-based cg*FEM and follows describing its *image-based* version in detail and how to combine them to include CAD models into the medical image. The third section contains analyses of reference problems used for the validation of the method whereas in the fourth one the method is applied