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Deformation analysis of brain regions

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Abstract

The analysis of 2D and 3D deformations applied to structures having non regular geometry is presented. Deformations are studied in order to understand complex dynamic problems coded into image sequences. In particular, methods have been developed suitable to control the reconstruction and the spatial deformation of cerebral structures, in their different aspects of morphometry, isometry and densitometry. Finally, a simulation process of brain deformation caused by a neoplasia in a real relevant clinical case has been performed.

Introduction

Within a finite, discrete and dense 3D space, expansive or contractile event of any object can generate variations of morphology and location of whatever adjacent or remote *embedded* structures. The characteristics of the deformations are related to many factors, like position and dimension of the perturbing event, its way of modification and also the structural properties of the space itself. The definition of analytical laws suitable to describe morphological transformation of structures submitted to complex perturbations is a relevant theoretical problem [1][2]. Usually, non homogeneous density features, morphological complexity and other constraints do not allow the problem be faced according to mere physical-deterministic criteria. In fact, many cases of real image processing are characterised by a set of mechanical properties (e.g., resistance or elasticity) which are partially or totally unknown and then a deformation process can be efficiently analysed using simulation models based on selected reference parameters.

In this paper, the problem of object deformation is studied considering three-dimensional geometric and densitometric models derived from image sequences. A reference space is defined starting from source images, regions of interest in this space are segmented, 3D interpolated and a set of objects is reconstructed. Finally, a 3D description of the objects themselves is obtained, based on regular meshes, to allow geometrical-topological quantitative analysis and shape manipulation. The study performed has been then applied to the problem of the evaluation of cerebral structures deformation when a perturbing event is made up of a growing lesion inside the brain [3] [4] [5]. In this case, a main problem is to re-map precisely 3D functional systems (e.g. the vision or language systems obtained from atlas or other reference images) into the locally deformed brain by examining CT or MRI image sequences of a patient acquired before and after surgical removal.

1. Object model generation

A complete morpho-densitometric and functional model of brain is determined by fusing several 3D data-sets obtained from different acquisition methods (usually CT or MRI and anatomical atlas). The global implemented procedure utilised for the analysis and the elaboration of both radiological and graphic images is composed of the following phases: a) *image acquisition*, to obtain the necessary input data-sets (brain radiological slices and brain sections from atlas plates, acquired according to parallel planes); b) *identification and segmentation* of the homologous anatomical regions in the two kind of images; segmentation of the functionally defined regions belonging to the atlas plates and (when morphologically localised) to the radiological sequences; c*) two- and three-dimensional interpolation* of the segmented objects, to define carefully the real geometry of the contours of the objects, in the image plane, and of the surface of the objects, in the space defined by all the image sequences; d) three-dimensional geometric model *reconstruction* of the morphological structures identified in the radiological and graphic images and of the functionally defined systems segmented from the images atlas plates. The surface modelling procedure provides a discrete representation of an object surface based on a mesh of polygons constituted by simple associated nodes and adjacency relations. In this phase also densitometric characteristics can be associated to geometry; e) *data integration* into a unique physical and logical description model. Interpolation and curve mapping operations are necessary to overlap an image of the atlas on the correspondent radiological image; interpolation and surface mapping operations are necessary to re-scale volumes to a unique 3D reference system. At the end of data integration, each point in the space has more attributes deriving from different properties of independent input data-sets.

By means of this methodology the correct knowledge of the location and dimension of structures, coming from different data-sets, is possible.

2. Simulation model and deformation law

After image fusion, the simulation of an arbitrary deformation process can be performed on a normal brain by the virtual introduction of an arbitrary mass. A main scope is to define the new location of neuro-functional structures previously localised in the normal situation.

The deformation model takes in account that an expansive process generates a force field acting both on near and far objects; in particular, a 3D radial force field is considered having its origin in the centre of mass O of the expansive process itself [6]. The force intensity in a point P depends on the distance OP and on coefficients derived from the resistance of the different zones crossed along the line OP. Every *displacement vector*, which define the new position of a point P after deformation, is characterised by an application point, a direction, a verse and a module. In particular, the module is calculated as a percentage of the radius of the expansive mass along OP. This percentage is function of an elastic law [7] whose parameters depend on the densities of the zones crossed by the radial force lines and on their morphology. These zones can be described by their contours which identify a 3D iso-surface when considering the whole sequence of images. Obviously, the direction of a selected displacement vector is the same of a line force and its verse is from the centre of mass of the lesion to the contour of the considered 3D space.

Then, in order to characterise the force field, another displacement vector can be selected in function of the local difference between the homologous structures extracted from the normal situation and the deformed ones.

The displacement vectors are individuated by a set of couples (p_i,q_i), where $p_i,q_i \in \mathbf{R}^3$ and each p_i is named *control point*. The deformation process is implemented by applying a transformation continuous function f: $\mathbf{R}^3 \rightarrow \mathbf{R}^3$ on every point x of the examined regions dependent on opportune coefficients, the distance between a point x and a control point p_i, the maximum distance between every point of the defined space and any control point p_i and an appropriate B-spline function [8].

3. An example of application

The described methodology has been applied to sequences of CT brain images of a subject affected by a growing intracranial lesion; in this case, the aim was to analyze the effects of the deforming process on the ventricular system. Two different scans of the same patient were acquired, before and after (6 months later) the development of a large neoplastic lesion.

Each CT scan, composed of 22 slices, has been 3D interpolated and pre-processed obtaining a new sequence of 211 images (340x270 pixels, 0.5 mm spatial resolution).

The effect of the deforming process calculated on the ventricular structure is shown in two homologous slices belonging to both sequences: Fig. 1 shows a section of the normal brain, while Fig. 2 shows the homologous section of the same altered brain.

Fig. 3 shows the result of the segmentation of the image in Fig. 1, where the radial force field originating from the centre of mass of the lesion is evidenced; finally, Fig. 4 shows the result of the deformation process computed on the right ventricle when the left ventricle is maintained unaltered but considered as a resistance region: the gray contour is related to the real case of Fig. 2, while the black contour is obtained by simulation.

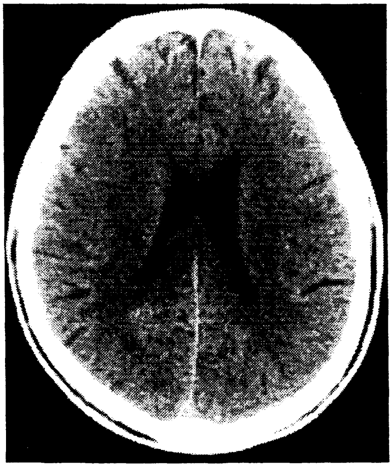

Figure 1

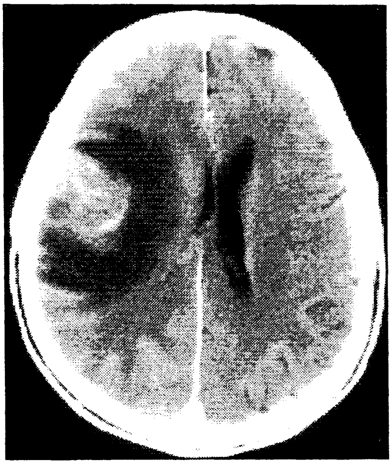

Figure 2

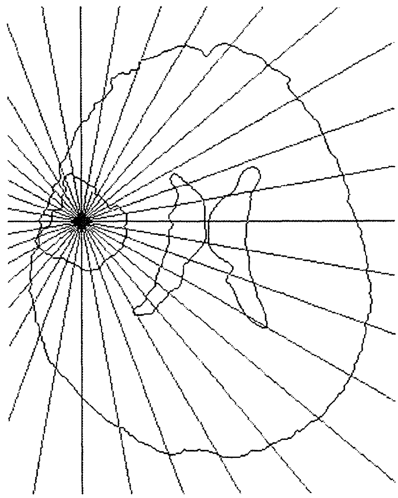

Figure 3

Figure 4

4. Conclusions

A general mathematical model of the brain permits to define geometric laws of shape variation also considering peculiar parameters inherent embedded structures. An extensive analysis performed in a large number of subjects is quite important to define correct deformation laws able to describe different conditions depending on the places of perturbing agents and on varying structural encephalic characteristics.

This study is a preliminary step towards the definition of a probabilistic deformation model which should consider progressive approximation criteria to single real cases of deformations evidenced by specific neuro-radiological cases. The laws able to precisely describe the modified morphology of regions, once applied to the geometric space of the whole object, might describe the new spatial configuration of the densitometrically homogeneous structures located among deformed iso-surfaces.

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